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# REMOTE MANIPULATION WITH TRANSMISSION DELAY

*by William R. Ferrell*

Prepared under Grant No. NsG-107-61 *by*
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Mass.
*for*

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ABSTRACT

If a remote manipulator is located at a great distance from a person using it and monitoring its activity, limited signaling speed will result in a time discrepancy between the operator's control activity and the feedback he gets concerning the response of the distant equipment. The work reported represents the results of a program of exploratory research into the effects of such a delay on an operator's ability to perform self-paced manipulation tasks with a manipulator which duplicates his hand motions.

Although previous research suggested that with a delay, time could not be traded to get accuracy, it was found that even complex tasks could be accomplished by adopting a simple strategy of performing the task by a series of discrete, open-loop movements. No evidence of "unstable" motions or of delay induced emotional stress was observed. Since this strategy was consistently used, it was found possible to predict task completion time in the delay case from measures of operator-manipulator performance when there was no delay.

Ability to perform without visual feedback, open-loop, was separately investigated. It was found that the number of open-loop movements needed for the task of moving a control from one position to within a given tolerance of another was not seriously affected by many linear and non-linear properties of the control. For a similar manual task, a statistical model, assuming independence of each move, and implemented by a Monte Carlo computer program, gave results corresponding generally with experiment. Data from using periodic stroboscopic illumination suggests that the number of flashes required to accomplish a visual-motor task is linear with flash rate--approaching open-loop performance at low, and normal continuous performance at high rates. The reasons for this are not known, but it may be indicative of a link between discrete and continuous motor performance.

ACKNOWLEDGMENT

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# 1. REMOTE MANIPULATION

## 1.1. The Need for Remote Manipulators

Manipulation is one of man's most salient characteristics. But, in expanding his sphere of action, man has found or created environments so hostile that to protect himself he must forego the intimate contact of direct manipulation and act, instead, with mechanical extensions of his hands through protective barriers of matter, of distance, and hence even of time. Men have always used tools to extend their reach, but only recently with the development of nuclear power and exploration of the depths of the sea and outer space has it become necessary to devise remote manipulators capable of operation at distances of many feet or many thousands of miles, and also able to perform a large variety of tasks, many of them unforeseen.

Repairing equipment and performing experiments in areas of intense radiation are examples of tasks which are now done with the aid of general purpose remote manipulators. There is already a pressing need for manipulators for search and salvage on the bottom of the sea, and in the near future the operation and maintenance of apparatus both in space and undersea will result in further requirements for remote extensions of man's hands as well as his sensors.

## 1.2. The Importance of Human Factors in Manipulator Design

One of the most fundamental problems in designing manipulators is that of achieving a compatible and harmonious relation between the apparatus and the operator who controls it. In order to design the system so that the operator performs effectively within it, the engineer will need an understanding of how people perform manipulative tasks--of how they program, monitor, and control their actions--and he will also need to be able to assess the effects of the equipment on these activities in order to predict system performance. There is relatively little theory to guide the engineer in these matters, and much remains to be done before both the nature of human manipulation and principles by which it may be extended to a remote environment are well understood.

## 1.3. Characteristics of Manipulation

Manipulation is a process by which physical objects are moved relative to an environment by an external, controlled agent. In ordinary manual manipulation, the controller is the nervous system and the agent is the hand. With an automatic manipulator, the controller might be a programmed computer, and the agent an electro-mechanical device.

Remote manipulation in the case of automatic equipment requires the extension of the links between controller and agent, the controller having to take into account any effects of the extension. Much the same is true of remote manipulation controlled by a human operator, except that the controller can no longer be considered as the nervous system alone, but is represented by a complete manipulatory situation as shown in Fig. 1. In such a case, there are two manipulations, one performed directly by the man in his communication with the machine, and the other performed by the remote agent. The fact that there are two manipulations, both of which must be successfully performed introduces a fundamental complexity and is at the heart of the problem of matching the man and the machine.

### 1.4. Modes of Operator Control

The allocation of the decision making and feedback handling functions of a manipulator system between man and machine is logically arbitrary and the entire continuum from an automatic device to manual manipulation is possible. However, it is useful to subdivide this range and consider three types of operator control, within-loop, supervisory, and automatic.

#### 1.41. Within-Loop Control

Manipulation under the direct control of a human operator requires that he be in the loop observing performance, deciding what should be done, and initiating all commands to the remote unit. This within-loop control generally provides the most versatility by allowing the operator both to modify strategies and goals in response to contingencies and to draw upon his own extensive experience with manual manipulation. Most manipulators in use are of this type.

#### 1.42. Automatic Control

When an operator does not participate in the actual manipulation at all, but initially programs and adjusts the system, control may be considered automatic. Automatic manipulators are not necessarily confined to rigidly executing a detailed set of commands, but may have extensive closed-loop control and decision-making capabilities of their own. The most notable example is the computer controlled hand devised by Ernst[1] which could respond to general commands such as

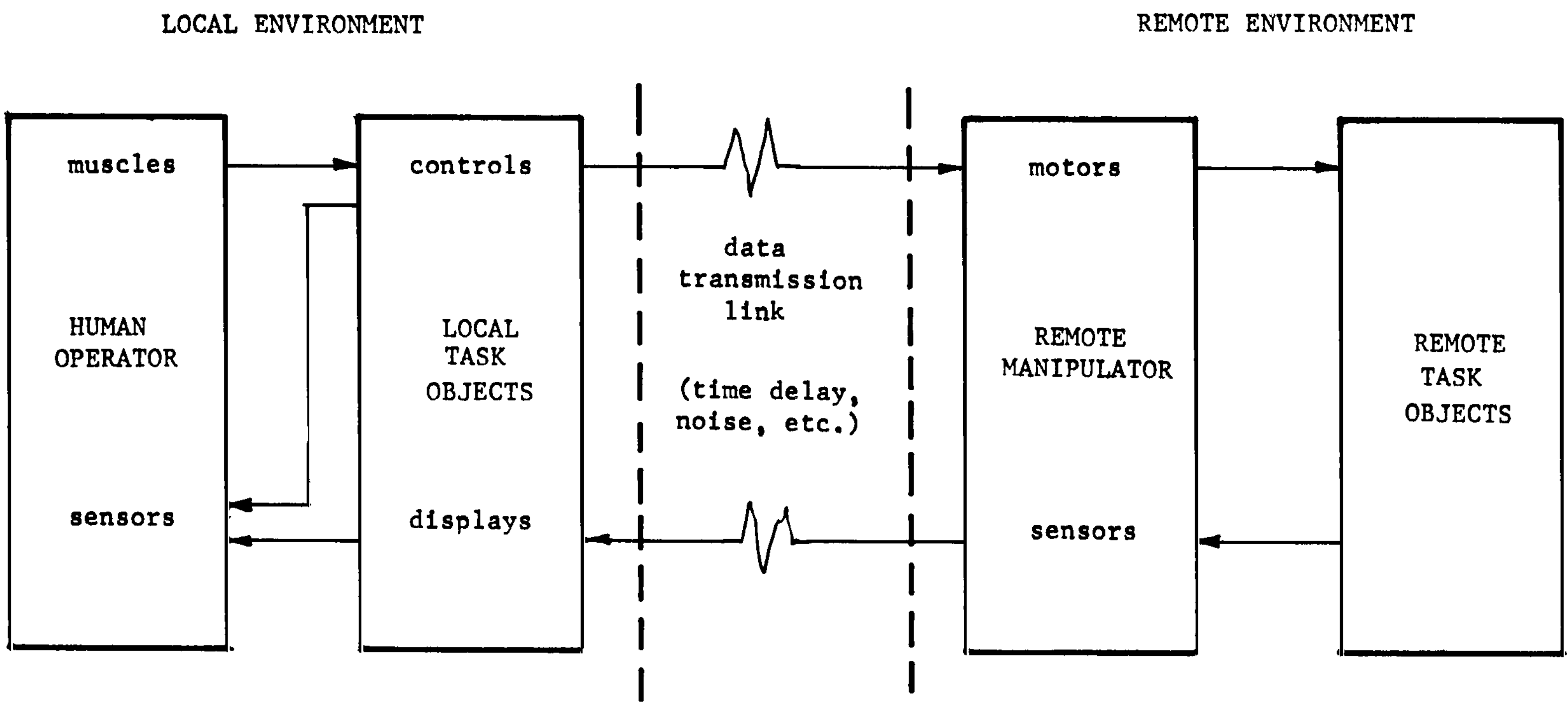



Fig. 1. Diagram of Remote Manipulation

"Find the blocks and stack them" with a sequence of actions which took contingent events into account.

### 1.43. Supervisory Control

Between automatic and within-loop control is a third category in which the decision function is shared by the machine and the operator, who commands complex, integrated responses and monitors performance in a supervisory way. Potentially this kind of control is of great importance since the best capabilities of both man and machine can be fully used.

## 1.5. Types of Manipulation Task

There is an important distinction to be made between two kinds of manipulation task, forced-pace and self-paced. Indeed, this distinction applies to all control situations involving a human operator. Self-paced tasks are those in which the only time-varying features are introduced by the operator. In forced-pace tasks, the timing of at least some part of the task is dictated by the environment. Within each category, one may further distinguish between tasks on the basis of whether a measure of error increases without bound if the controller stops functioning and holds its output constant[2]. If the error doesn't limit, the task would be classified as unstable, otherwise it would be stable.

Tracking in response to a time-varying input is a good example of a forced-pace task. A laboratory tracking situation is usually stable in the sense that if the subject stops tracking the error may become large but it reaches a limiting value. The tracking involved in driving a car is, however, unstable, since a "catastrophic" error will eventually occur if the driver relinquishes control.

An example of a stable self-paced task is positioning an object on a table. If the operator stops, the task stops and remains the same until the operator continues. Unstable self-paced situations are less common. Balancing an object is an instance. There is no external forcing function, but if the operator ceases to make the necessary corrective movements the error will increase, in effect, without limit. Only with tasks in the self-paced stable category can one trade off between time and accuracy.

## 2. REMOTE MANIPULATION WITH TRANSMISSION DELAY

### 2.1. Delay-Lag Distinction

It is important to distinguish between a delay and a lag. These terms are often used interchangeably to indicate the response characteristics of either a perfect transmission line with limited propagation time or a dynamic system with capacitive or inertial elements. In the present context, the term delay will refer only to pure transmission time, and lag will indicate only the tendency of a system not to respond immediately to an input due to other dynamic characteristics, i.e. its behavior as a low-pass filter.

Except when all the frequencies of interest are very low, the distinction between delay and lag is of considerable practical importance for systems controlled by a human operator. For example, the output of a first-order system can be prevented from reaching its final value by an input in the opposite direction. If the system has just a pure delay, however, countermanding an input in this fashion is not possible; whatever the input, it will appear in the output after one delay time.

### 2.2. The Effects of Delay in the Closed-Loop System

If a delay, T, is introduced at any point in a closed-loop system, such as is shown in Fig.2.1. and T is much shorter than half the period of the highest frequency to which the system responds, $\omega_h$, then the effect will be mainly a slight time discrepancy between output and input. However, if the

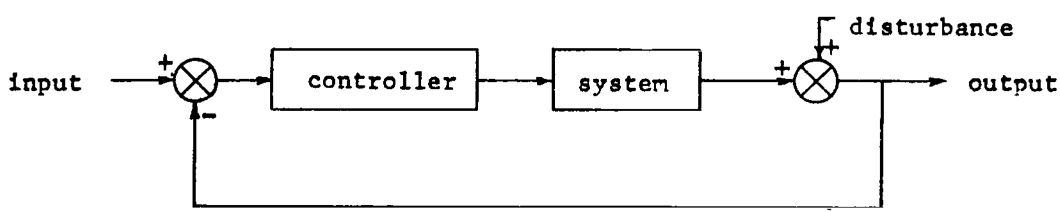



Fig. 2.1. Closed-Loop Control System

delay, T, is greater than half the period at frequency, $\omega_h$, then there can be an effective component of the input or of the disturbance whose frequency, $\omega$, is $\frac{n\pi}{T}$ (n an odd integer). For this frequency component, the error input to the controller will be completely out of phase with either the actual error, if the delay is in the feedback path, or with the corrective action of the controller if the delay is in the forward path. In either case, the controller will tend to correct in the wrong direction, accentuating the error. If the forward gain of the system for the component with frequency $\omega$ is greater than unity, and this would be the usual case if the system without the delay had a good response, then the tendency toward over-correction would result in instability. Depending on the system, the introduction of lags can have a similar result.

To some degree, the effects of delay can be compensated for in the design of the system by a reduction in gain, an increase in damping, or by using methods for predicting the correct signal from its delayed counterpart. For forced-pace, or for the self-paced unstable situations, all of these techniques can prevent the system itself from becoming unstable,--a system with no output being perfectly stable, of course,--but methods involving prediction of some kind permit both improved stability and improved performance. However, prediction breaks down for delays which are larger than the temporal spread of auto correlation in the input. On the other hand, in self-paced stable situations the controller can modify the rate at which input is accepted and thus effectively change the input spectrum to achieve any desired degree of stability and accuracy at the expense of increasing the time required to complete the task.

## 2.3. Studies of Human Performance with Delayed Feedback

### 2.31. Manual Tracking with Delayed Visual Feedback

Manual tracking was one of the first areas in which human performance with delayed feedback was studied. In 1945, investigators at the Foxboro Company in Massachusetts[3] found that delaying the visual feedback by 0.1 sec slightly decreased accuracy in an aided pursuit tracking task.

Warrick[4], in 1949, treated delay time as an independent variable in a compensatory tracking experiment. The error signal was recorded on a strip of chart paper and the delay was obtained by allowing the operator to see only a transverse strip of the chart an appropriate distance downstream from the pen. Warrick's hypothesis that accuracy in terms of time on target would be a linear function of delay was not borne out. Most recently, Adams[5], using a pursuit tracking task in which the display of both the input signal and the feedback are delayed, has found that integrated absolute error is approximately linear with delay.

All of these tracking situations were forced-pace, and naturally the input spectrum had an important effect on performance, as Adams[5] found. If the periods of the high frequency components of the input are much less than the delay time, T, then the value of the input at time, t, will be hard for the operator to predict from the values of the input and its derivatives T seconds earlier. Alternatively if T is short in comparison with the periods of the high frequency components, prediction will be easier since there will be little change over the delay interval. If the product of input band width (the band-width of the signals of importance) and delay is sufficiently high, then with forced-pace tracking the input cannot be followed adequately even if the closed loop is stable. One would expect better control with self-paced performance under delay than with forced-pace.

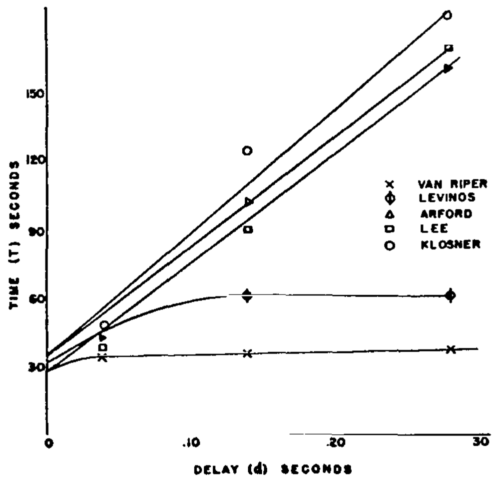
### 2.32. Delayed Auditory Feedback

In 1950, Lee[6] first called attention to the phenomena associated with delayed auditory feedback. It had long been known that it was annoying to a speaker to have a public address system placed so that he could hear his own words return a moment after uttering them. Lee found that if speech were delayed a few tenths of a second and returned to the ears by earphones at a level sufficient to mask the immediate feedback conducted through the speaker's head, the speaker would tend to stutter, to be emotionally upset and to change the rate and pitch of his voice. He reported[7] that stuttering could be eliminated only if a proper cadence were observed in speaking with the delay. Lee[7] proposed that these effects could be explained in feedback control terms and also suggested delaying both aural and visual feedback as a means of studying the manner in which motor activity is controlled by the brain.

The model Lee proposed for the control of speech involves a hierarchy of feedback loops. At the lowest level is articulation or phoneme control with mainly kinesthetic feedback. Next are loops, closed through the aural sense, which govern syllable production, words, and, at the highest level, thoughts. The lowest loop would be little affected by delaying the auditory feedback, but the voice or syllable loop would be. From this model, Lee derived an expression for the total speech time necessary if stuttering is to be avoided:

$$T = t + nd$$

where T is the total time, n the number of phonemes and spaces, t the average time when there is no delay, and d is the delay time. Results from the model and experiment are compared in Fig. 2.2. The two subjects whose data does not fit the linear relation were presumably able to ignore the delayed feedback.




Time required to read a text of 437 units (372 phonemes plus 65 spaces).

Fig. 2.2. Speaking Time as a Function of Delay (from Lee[7])

The model indicates, although Lee did not explicitly say so, that for accurate speech it is necessary to wait a delay time following pronunciation of a phoneme so that the aural feedback monitor will permit the next phoneme to be produced, otherwise repetition, i.e. stuttering, will occur.

Since 1950, much work has been done on delayed auditory feedback from both vocal and non-vocal tasks such as rhythmic tapping. It has been found by Fairbanks[8] that longer delays, above 0.2 sec, have a decreasingly serious effect upon speaking time and errors. This is due to the ability of the speaker to dissociate his performance from the feedback he gets and to act in an open-loop manner. One would certainly expect this since speaking is a self-paced stable task which doesn't absolutely require auditory feedback. It can be performed more or less correctly with a short delay but at the expense of time since one cannot generally ignore feedback unless the delay is fairly large. If the delayed feedback is attended to and there is no compensatory slowing down, the speech pattern is seriously disrupted--in effect an instability appears. Delaying the auditory feedback from rhythmic tapping can produce a similar breakdown[9].

### 2.33. Delayed Visual Feedback from Writing

Handwriting is analogous to speech in that it is self-paced, can be performed with only kinesthetic feedback, and is normally carefully monitored. One would thus expect that delaying the visual feedback from writing would produce similar results to those got by delaying the auditory feedback from speaking. In 1959, van Bergeijk and David[10] examined this problem and found that handwriting with delayed visual feedback indeed showed changes analogous to those of speech provided that the feedback was attended to and the task not done open-loop. Kalmus, Fry, and Denes[11] and later Smith, McCrary and Smith[12] substantiated the findings. Delay of visual feedback resulted in repetition, omission and substitution of letters, less accurate writing, and occasioned emotional disturbances indicated by irritability and the like.

### 2.34. Delayed Visual Feedback from Tracing Tasks

Kalmus, Fry, and Denes[11] were the first to study tracing tasks with delayed visual feedback--tasks which could not be successfully accomplished with only kinesthetic information and which were, for that reason, much more like manipulation. Their apparatus consisted of a Telautograph, a remote writing instrument, with delay provided by a rotating bank of capacitors fed with the command voltage at one point of its cycle and read from at a later point. They measured both the time necessary to perform the tracing tasks and also the area between the master and the tracing.

Their results indicated to them that

> "Duration of writing and 'error area' increase with the amount of visual delay--and though the subjects manifestly varied their attempts to overcome the difficulties of the delay--we believe that the 'trading' of speed for error area or vice versa was in fact not very successful. Consequently the error area is by itself a good measure of the effects of visual delay and the product of error area and time only very slightly better".[13]

This observation did not auger well for remote manipulation wherein certain limits on accuracy must be maintained if the task is to be performed at all.

In 1960, Smith, McCrary and Smith[12] reported much the same experiments as did Kalmus, Denes and Fry. They used a system of televising the subject's activity, recording the image on tape and playing it back 0.52 seconds later to a monitor observed by the subject. As well as writing and drawing, they investigated tracing through a maze, dotting circles and tracing a star pattern--all of which had explicit error bounds visible to the subject.

Smith's[14] conclusions also were not auspicious for remote manipulation. He states that

> "The professional adults who acted as subjects in this experiment found that introduction of a 0.52 second delay between movement and visual feedback made their performance inordinately difficult and frustrating. The simplest of tasks, such as placing a dot in the center of a circle, was nearly impossible to achieve with any reasonable degree of accuracy or movement control. Any kind of localizing movement, simple or complex, demanded extraordinary effort and had but poor success. Placing and tracing motions that are normally fast, uniform, smooth, and highly precise became erratic and jerky regardless of all attempts to control them. Tracing movements that demand continuous visual guidance became very noticeably oscillatory, and even the more discrete movements were similarly affected".[15]

Smith[14] also observed that the subjects experienced emotional as well as motor disturbances. In other words, instabilities were seen analogous to those one would expect in a servo system with delay in the loop.

### 2.35. Delayed Visual Feedback in Steering Remote Vehicles

The surveyor project, proposed by NASA, in which a vehicle would be landed on the moon and remotely driven by an operator on earth, stimulated considerable interest in the effects of transmission delay on driving performance, and in techniques for assisting the operator. Delayed driving differs significantly from tracking with a delay in that the driver has a preview of the road ahead and hence need not predict the future input solely from local time derivatives.

Adams[16], in 1961, was the first to make a full-scale study of the problem. He constructed a constant speed vehicle which was steered by an operator viewing the picture from a television camera on the vehicle. A magnetic tape recorder with a tape loop provided a delay between the driver's steering movements and vehicle response. The results of Adams' experiments showed that driving performance strongly deteriorates with increasing delay--an effect made even more serious by high speeds, increased course complexity, limited television field of view or sluggish vehicle response.

A study by the Grumman Aircraft Company[17], using a jeep driven remotely with a delay of 2.5 seconds, also indicated the important dependence of accuracy on speed and on the complexity of the road. The findings of both Adams and the Grumman investigators are in general accord with the results of the tracking studies mentioned earlier.

In neither of the delayed driving experiments just cited could the operator control the speed of the vehicle. This is in line with the need to keep the power consumption of a lunar tractor at a low level, but the operators task is thus made more difficult by being forced-pace. Chanet, Freeberg, and Swanson[18] used a remotely operated miniature vehicle with a delay of 3.0 seconds in an experiment to compare the effectiveness of a "bird's eye" or overhead view with a "windshield" or forward view display. The operator could stop, or could go at either half or full speed as well as steer. The results appear to indicate that (for the windshield viewing condition) the option to stop was used to get more accuracy at the expense of total driving time.

To improve the operator's ability to control a vehicle when there is a delay, Braisted[19] devised a predictor which calculates the position of the vehicle that would be observed one loop delay hence relative to the position observed "now", and which displays this position in correct perspective and orientation as a bright ellipse (superposed on the view of the landscape) on the operator's television monitor. The ellipse responds immediately to steering commands, giving the operator feedback which is not delayed. The effect is like driving a car by observing the road from a television camera rigidly mounted on a trailer behind. The "trailer's" distance behind is jointly proportional to the delay and the speed. Braisted found that using the predictor one could drive at moderate speeds almost as well with a delay as without. A predictor of this sort can be effective only if the operator can see the road ahead.

### 2.36. Implications of Previous Studies of Delayed Sensory Feedback for Remote Manipulation with a Delay

All of the investigations cited above indicate that delayed feedback is detrimental to human performance unless the task can be accomplished open-loop and the operator is able to ignore the delayed information, or unless the task is such that a predictive display is possible.

Remote manipulation tasks, in nearly all practical situations, are self-paced and allow the operator precognitive information, i.e. preview. Moreover, manipulation requires a sequence of operations which must at least meet fixed accuracy criteria if the task is to be accomplished. In view of the studies of human performance with delay reviewed above, it would seem evident that an operator continuously controlling a remote manipulator through a delay would be unable to achieve sufficient accuracy to perform any but the simplest tasks unless either 1) he could trade off time for accuracy or 2) he were assisted by a predictor display.

Of the reports cited, only two, Lee[7] and Chanet, Freeberg, and Swanson[18] give any indication that accuracy may be obtained at the expense of time in a self-paced task, and the tasks considered were not similar to manipulation. The investigators who have studied tracing tasks, Kalmus, Fry and Denes[11], and Smith, McCrary and Smith[12], explicitly mention that error increases with delay in spite of efforts by the subjects to be more accurate. Trading time for accuracy in delayed remote manipulation would not seem a likely possibility on the basis of work reported thus far.

The other alternative, a predictor display, would be difficult to implement if it had to be relied upon to carry the full burden of feedback; for when the manipulator is transporting an object, a tool for example, the critical information about the location of parts of the tool is not just a function of the manipulator shape and position but also of the shape and orientation of the tool. Thus the predictor would have to predict and display not just the manipulator configurations but object configurations as well. This is probably too stringent a requirement to be met within reasonable limits upon cost and complexity.

In order to assess the feasibility of within-loop operator control of remote manipulation when there is a transmission delay, it is necessary to re-examine the possibility of achieving accuracy at the expense of time--to investigate actual manipulation with a delay to determine whether the operator can maintain reasonably stable and accurate performance. If he can, then the possibility of giving him the assistance of some form of predictor display may have practical significance, since the predictor will not have to provide all the feedback upon which the operator must base his decisions.

## 3. PROBLEM STATEMENT

The research to be reported was undertaken with the objective of obtaining useful engineering information concerning the ability of an operator within the loop to use a remote manipulator to perform self-paced stable tasks when there is a transmission delay. Along with this specific engineering emphasis, there has been an effort to relate findings, whenever possible, to other work in the field of human performance.

The specific questions which have arisen in the course of the work, and to which answers have been sought through experiment are stated in subsequent sections, however most of these questions can be grouped under the following headings.

1. Can a person in continuous control of a remote manipulator effectively perform manipulation when there is a delay in the loop?
2. When using a manipulator with a delay, will a person make erratic and "unstable" movements, and will he show signs of emotional stress?
3. If manipulation can be performed with a delay, by what strategy is it accomplished?
4. Will people permitted practice with a delay adopt an adequate strategy on their own?
5. Can task completion time in the delay case be predicted from performance measures taken when there is no delay?
6. What factors govern task completion time when there is a delay and what aspects of sensory-motor skill are most involved?
7. What properties of a manipulator master control most affect performance in the delay case?

# 4. EXPERIMENTS WITH DELAYED REMOTE MANIPULATION

## 4.1. The Remote Manipulator Used in the Experiments

A simple servo-driven manipulator was assembled for the purpose of investigating remote manipulation with a transmission delay. The two fingers of the master hand could be opened and closed and moved in a horizontal plane. The fingers of the slave hand performed the same motions in response. The signals from the master to the slave could be delayed by means of a tape recorder. In spite of the minimal number of degrees of freedom for which it was given the name "minimal manipulator", it could be used for a large number of tasks requiring grasping, positioning, and rotating objects.

The slave unit was a large, servo-driven x-y plotter and function generator. On its moving carriage was mounted a "hand" consisting of one fixed and one servo-driven "finger". The hand could be moved 13 inches in either direction, and the fingers opened to 2 1/4 inches.

The master control was specially constructed for the purpose. Its "hand" also could be moved 13 inches each way and its "fingers", held between the operator's thumb and forefinger and spring loaded open, spanned 2 1/4 inches. A schematic diagram of the master and slave is shown in Fig. 4.1.

The position of the master hand was indicated by the voltage picked off a pair of linear potentiometers, and the finger position was given by the voltage from a rotary potentiometer geared to the master fingers. These three voltages were pulse modulated, recorded, played back, demodulated and finally amplified before being used as command signals for the servos of the slave hand.

The delay time was adjusted by positioning the center one of three capstans over which the tape passed between the record and read heads of the tape recorder. The size of the bight thus formed determined the delay, the tape travel time from one head to the other. The smallest delay possible was 0.3 seconds. The longest provided for was 3.6 seconds.

Low frequency noise from the tape drive presented a serious problem, which was largely overcome by subtracting from the x and y signals the pure tape noise from the one unused channel of the 4-channel recorder. High frequency noise was reduced by filtering, at the cost of somewhat reduced system response.

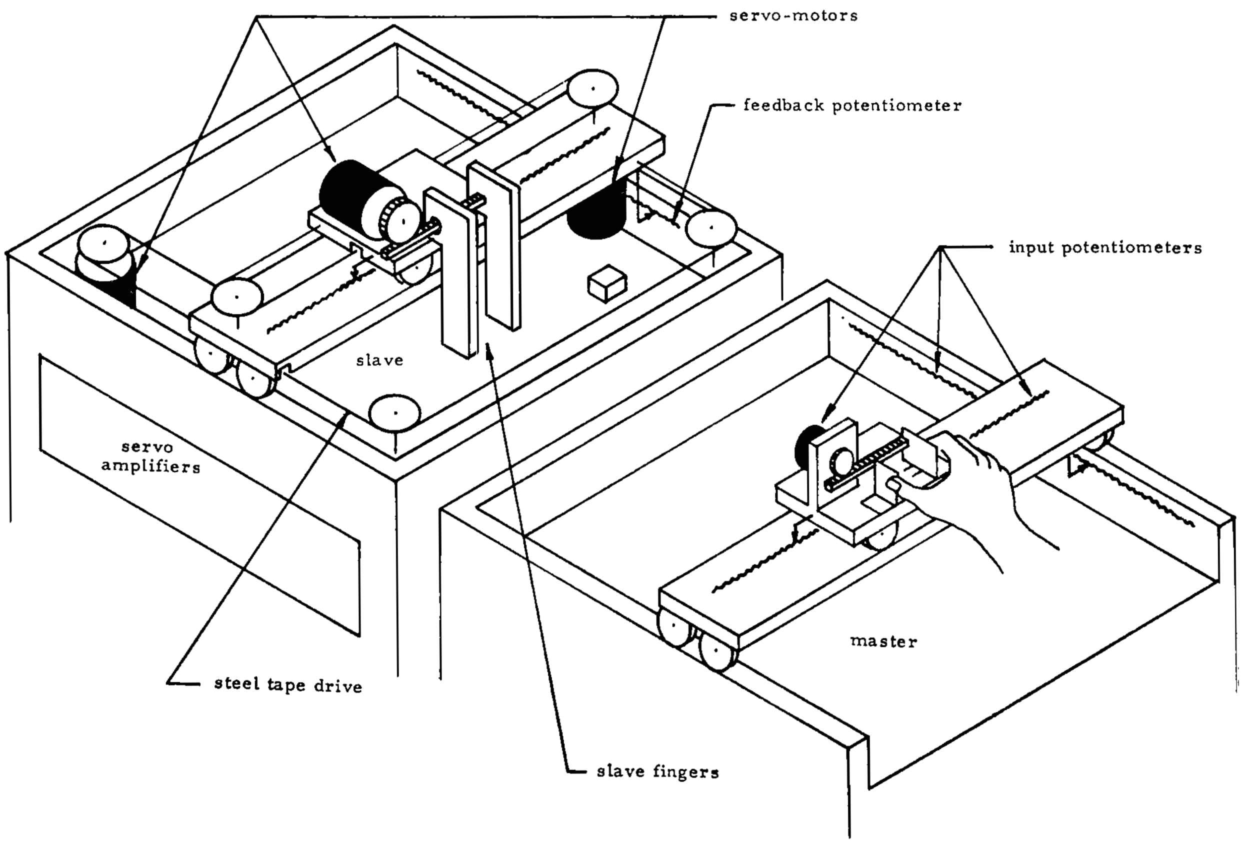



Fig. 4.1. Schematic Diagram of the "Minimal Manipulator" (not to scale)

When using the manipulator, the operator stood with the master control before him, looking over it to the slave hand, 4 to 5 feet from his eye, as shown in Fig. 4.2. He held the master hand in his own, as in Fig. 4.3, moving it or opening or closing the fingers to make the slave do likewise. An opaque shield was placed over the master control preventing the operator from seeing his own or the master hand. This ensured that visual feedback came only from the slave hand. Were the barrier not there, the operator might make use of accidental bench marks for positioning in repetitive tasks, and generally use the master hand as a kind of predictor display.

Although the delay was placed only between the master and slave, the result, insofar as the operator is concerned, is precisely the same as if the slave were at a very great distance, with half the delay in the forward and half in the feedback path. This is true because regardless of how the delay is apportioned between paths, any movement by the operator will appear on his display a loop delay later since the signals must go round the whole loop. For the same reason, the division of the delay will not affect the relative times of occurrence of an event at the remote end and the remote hand's response to it.

The dynamic response of the slave hand to movements of the master control, when there was no delay, was generally good. A slight lag was noticeable when making rapid movements, but with only a small amount of practice operators could use the equipment easily and confidently. Fig. 4.4 gives Bode plots for gain and phase in both the x and y directions. The y direction was right and left for the operator. The plots are for a command amplitude of 4 inches. The results for an amplitude of one inch differ only beyond 1.2 cps.

### 4.2. Strategies for Trading Time for Accuracy in Remote Manipulation with Delay (Preliminary Experiments)

The minimal manipulator was first used for a number of informal experiments with delay in which blocks were grasped, rotated and aligned in various patterns.

It became clear from this preliminary work that even tasks requiring great accuracy could be performed with a delay, but at the expense of considerable time. It was also clear that if no strategy for coping with the delay were used, i.e. if the delayed visual feedback were treated as if there were no

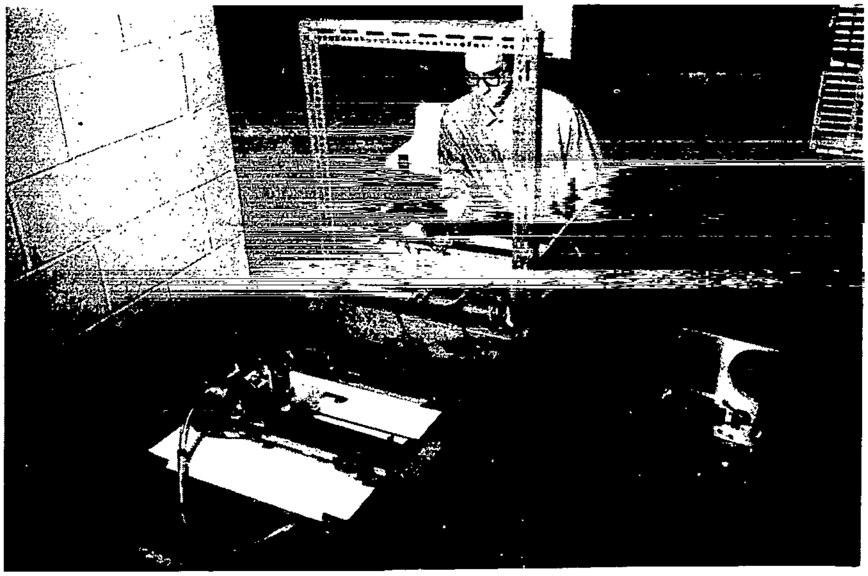


Fig. 4.2. Remote Manipulator with Tape Delay

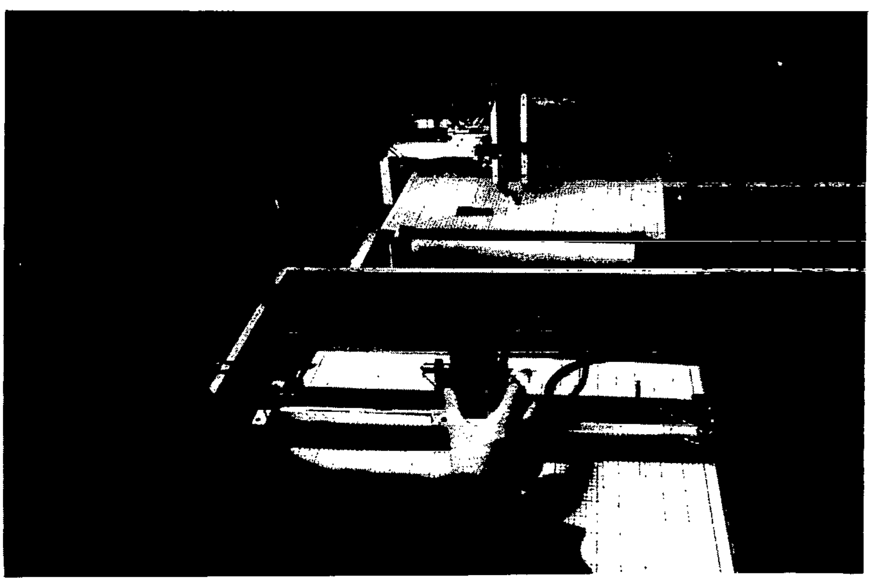


Fig. 4.3. Remote Manipulator Master and Slave Hands

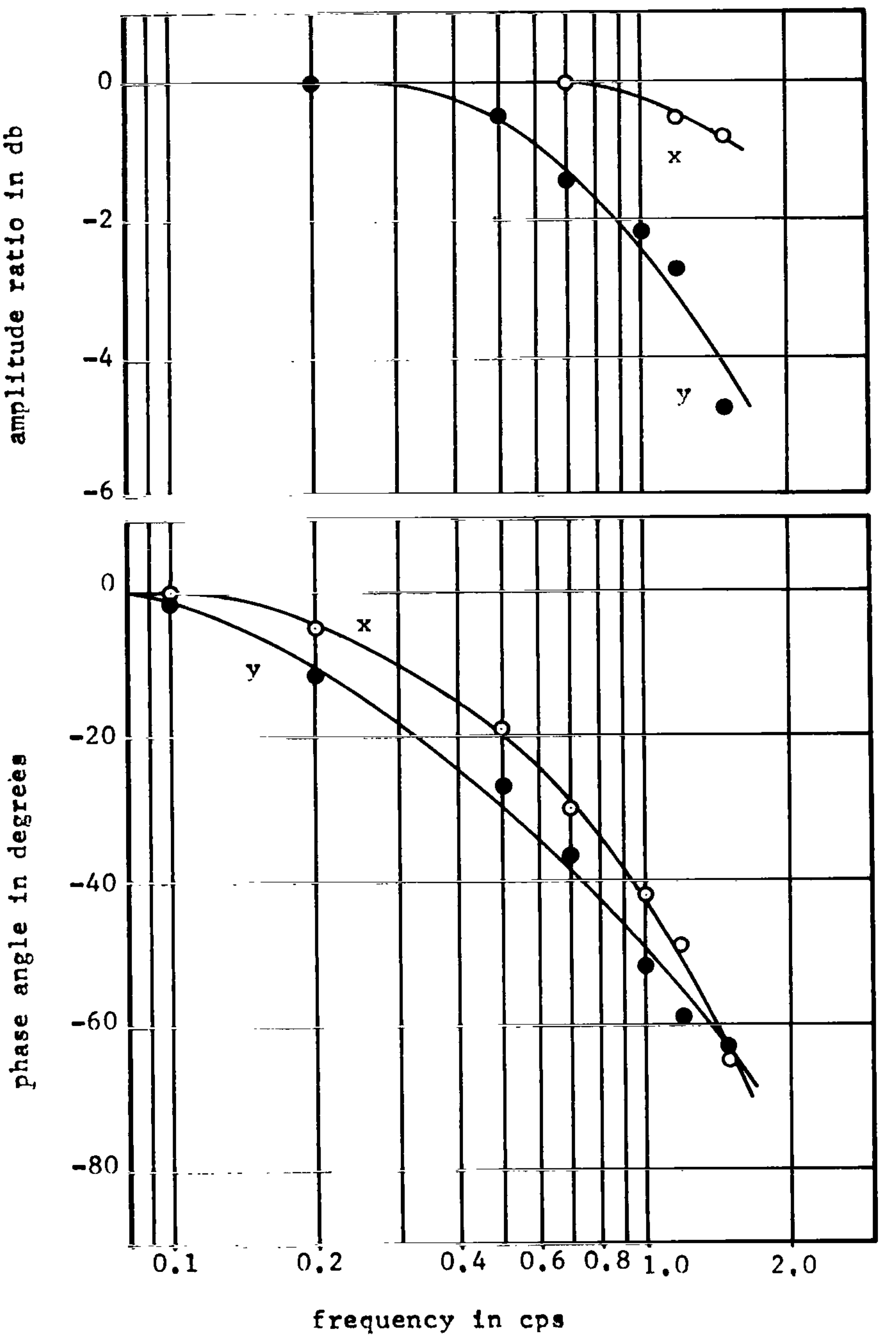



Fig. 4.4. Manipulator Frequency Response

delay, then performance exhibited the same inappropriate corrective movements, the same signs of "instability" that were observed by Kalmus, Fry and Denes[11] and by Smith, McCrary, and Smith[12] in their tracing experiments.

There appeared to be only two strategies, used separately or in combination, by which an operator could move the slave hand from one position to within an arbitrarily small tolerance of another.

1. The first strategy was to move slowly. At very low frequencies the behavior of a system with delay is very close to that for one with no delay. Thus, if one moves very slowly, the feedback from observing the delayed slave hand is almost correct. In order to decrease the feedback error, or to maintain the same error at a longer delay, one must move still more slowly. In using this technique to reposition the slave hand, an operator typically starts toward the new position at such a speed that the slave is fairly far behind, then slows down as the new position is approached, finally oscillating very slowly about the final position and stopping when he thinks he is within tolerance. He then waits a delay time to see if he actually is in the prescribed region. If he isn't, a slow correction is made.

This method works, but it has distinct drawbacks:

a) It is difficult to estimate the future position of the slave hand a delay time ahead even at low speeds, since one must keep track continuously of the movements of one's hand over the past delay period. If one moves too rapidly or loses track of previous movements, erroneous corrections are made and performance deteriorates.

b) The same symptoms of frustration and emotional strain noted by others in situations with delayed sensory feedback were also observed.

2. The second strategy for accurately repositioning the slave hand is for the operator to move the master hand open-loop, i.e. using only kinesthetic feedback, to his best estimate of the correct position and then to stop and wait a delay time until the slave hand has caught up. At this point the visual feedback is correct, and the operator can observe any remaining error and repeat the sequence until the required tolerance has been achieved.

This "move-and-wait" strategy has several advantages over the slow movement strategy:

a) It was invariably found to be more rapid and more accurate than moving slowly.

b) The method itself is independent of both the delay and the accuracy required.

c) Instead of demanding of the operator an unusual change in the ordinary pattern of sensory motor activity, this method requires only that he make movements without visual feedback--which he does to a considerable extent in manual manipulation.

d) The technique is simple and doesn't require the operator to combine delayed visual feedback with kinesthetic feedback to estimate his actual position on a continuous basis.

From the preliminary experiments, it appeared that the move-and-wait strategy would be the one that an experienced operator would adopt. In this connection it is interesting to note that others have observed a tendency for subjects working with delayed feedback to make discrete responses. Smith[12,14] found this with his subjects, although none apparently had sufficient practice to develop a consistent strategy enabling him to perform his tasks. Performance on tracing a star pattern with 0.52 sec. delay was so poor it couldn't even be scored[14]. Adams'[5] data for tracking with delay shows that at the 3.0 and 6.0 sec. delays subjects frequently alternated discrete responses with periods of waiting. Braisted[19] observed similar behavior.

> "When driving with a signal transmission lag and no predictor, the drivers found it helpful to steer in a burst of activity. Here they would command a large turn and then wait, if possible, to observe the results before making the next turn. Driving performance improves when they have an opportunity to separate the job into a series of isolated maneuvers".[20]

This opportunity exists only to a limited degree in forced-pace tasks such as tracking. Self-paced tasks, which include most of manipulation, can be reduced to as many components as necessary.

## 4.3. Completion Time as a Function of Delay and Task Difficulty for a Simple Task (Experiment 1)

### 4.31. Objectives

The first experiment was planned with the following objectives in mind:

1. To determine what kind of strategy would be adopted by an experienced operator.
2. To see if the performance would exhibit unstable or oscillatory movements.
3. To see whether the operator would show signs of emotional strain.
4. To determine whether an informational measure of task difficulty for simple tasks which is suitable for ordinary sensory-motor activity would also apply to remote manipulation with a delay.
5. To determine what consistent relations, if any, obtained among completion time, task difficulty, and delay.

### 4.32. Design of the Experiment

The experimental task required the operator to move the slave hand, on the word "go", to the right from a fixed starting position until its open fingers were aligned with the sides of a small block. He then had to grasp the block by bringing the slave fingers on either side of it and closing them. The task is diagramed in Fig. 4.5. A continuous pen recording was made showing the

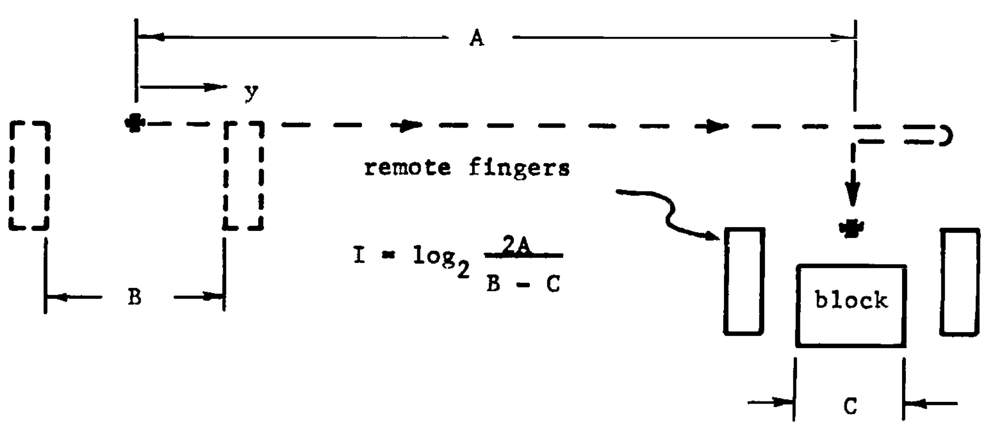



Fig. 4.5. Diagram of the Task Used in Experiment I

command to start, the lateral positioning motion of the slave hand, and the motion of the slave fingers. Following the work of Fitts[21,22], an index of task difficulty, I, in information units was chosen, and is defined as

$$I = \log_2 \frac{2 \times \text{distance moved}}{\text{final tolerance}}$$

where final tolerance is the difference between the width of the block and the distance between the fully open fingers of the manipulator. As a check on the suitability of I as a measure of difficulty, three movement distances were used: 4, 6, and 8 inches. The manipulator fingers opened to 2 1/4 inches, and block sizes were chosen to give I values of 3, 4, 5, 6, and 7 bits at each distance. Three values of delay were introduced: 0.0, 1.0, 2.1, and 3.2 seconds.

At each delay the subject was presented with each of the 15 distance-tolerance combinations 10 times in random order. He was instructed to perform the task as quickly as possible without moving the block before grasping it. When the block was moved prior to grasp, the trial was repeated, and an error was scored. There were four sessions, each confined to one delay, and the delays were taken in increasing order.

Practice consisted of performing the experiment as outlined, except that each of the distance-tolerance combinations was presented three times for a total of 45 performances at each delay.

The experiment was performed twice; first with a subject, J.K., who had had considerable experience with a similar task during the preliminary experiments, and next with a subject, E.C., with no prior experience. Both subjects were male engineering students. Neither was coached or instructed regarding his strategy.

4.33. Results

The time from the word "go" until the manipulator fingers began to close was obtained from the chart record, and is designated completion time. The results for both subjects are shown in Fig. 4.6, a plot of task completion time on a logarithmic scale vs. the index of task difficulty I. The only significant effects revealed by an analysis of variance were the main effects of I and the delay time and the interaction of these. Since the effect of distance fell short of even the 10 per cent level of significance for both subjects, the

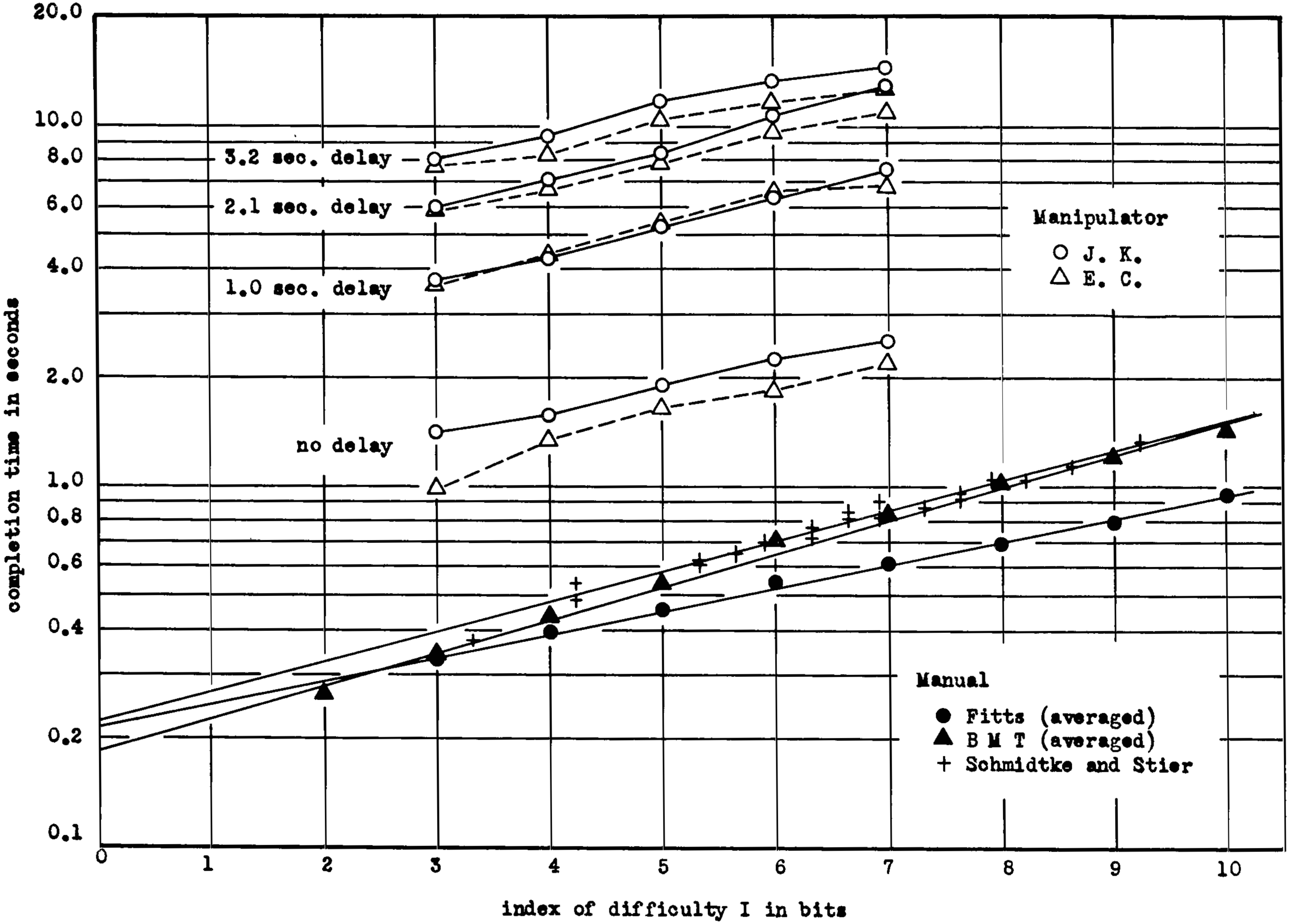



Fig. 4.6. Completion Times from Experiment I with Data from Manual Tasks for Comparison

results for the different movement distances were averaged at each value of I. Thus, each experimental point in Fig. 4.6 represents the average time for 30 trials. Average completion time is shown to follow a consistent logarithmic relationship with I.

For comparison with other tasks requiring accurate movements but not performed with a manipulator, and to indicate the usefulness of I as an index of task difficulty, Fig. 4.6 also shows data from other sources. The three sets of points are for 1) Fitts' data[21] for as rapid as possible pin transfer, 2) Schmidtke and Stier's data[23] for touching a circular target at sustained rates, and 3) values for class C arm reach with final accuracy obtained from the published tables of the Basic Motion Time Study predetermined time system[24]. The points from Fitts and the BMT system are averages of times at the several different distances and tolerances for which I is the same. Each point for the Schmidtke-Stier experiment represents a different combination of distance and tolerance.

Errors, i.e. occasions when the block was moved before being grasped, accounted for only 6.1 per cent of the trials for J.K. and for 8.6 per cent for E.C. Most errors occurred when the slave fingers were being brought on either side of the block. The number of errors was significantly greater at higher values of I. The errors that did occur were often grouped. Thus the likelihood of an error was greater when the preceding trial was in error than when the preceding trial was correct. The number of errors decreased with delay, presumably because of practice, until at the 3.2 sec. delay there were fewer errors than with no delay.

4.34. Discussion

In answer to the initial questions, the following observations may be made:

1. Both subjects adopted, independently and without coaching, the move-and-wait strategy and both maintained it consistently. This is clearly shown by the pen recordings of the lateral motions of the manipulator hand. Since subject E.C. had no previous experience with the apparatus, it was possible to record his initial attempts at positioning and grasping the blocks during his first practice run with delay. As the records show, he first tried moving slowly but soon tried moving and waiting, and by the end of the practice session he had adopted the latter method exclusively. Typical records are

shown in Fig. 4.7 to illustrate the change in behavior during the first practice at 1 sec. delay.

2. During the experiment there were no unstable or oscillatory movements, a fact presumably due to the consistent use of the move-and-wait strategy.

3. Both operators found the work tiring and difficult, but neither showed any outward signs of emotional strain or upset. The most onerous aspect of the job appeared to be due to the design of the master hand which required a slightly awkward grip.

4. The index I appears to be a consistent measure of task difficulty for remote positioning with a delay just as it is for manual positioning without delay. The completion time is strongly a function of I, and there is no consistent effect attributable to distance, as was shown by the analysis of variance. Further, if distance has no effect then tolerance must not either, since at a given I value the two are strictly correlated. For confirmation of this, however, one may compare all the cases in which the tolerances are the same. For the 4-inch distance, the I values of 3, 4, 5 and 6 have the same tolerances as the 8-inch distance. Thus taking the three delays and the no delay case, and the two subjects, there are 32 pairs of average times that can be compared. If tolerance has no independent effect then the times from the 8-inch distance will be uniformly higher since they represent a higher I value. Of the 32 pairs, only three show a higher time for the 4-inch distance; for the remaining 29 the time for the 8-inch distance was greater, as expected. It is clear, then, that I is a far better index than either distance or tolerance alone.

5. There appears to be in Fig. 4.6 a consistent linear relation between the log of the completion time and the index of difficulty at each delay for both subjects.

That the apparent effect of delay was different for J.K. and E.C. is probably not due to the delay but to the fact that the order of delay sessions is confounded with delay. J.K. had had the benefit of rather extensive prior practice in a similar experiment while E.C. did not. The differences might consistently be interpreted thus: E.C. is better at manual skills as evinced by his better times in the easily learned no-delay condition, but with greater practice with the move-and-wait strategy he increasingly

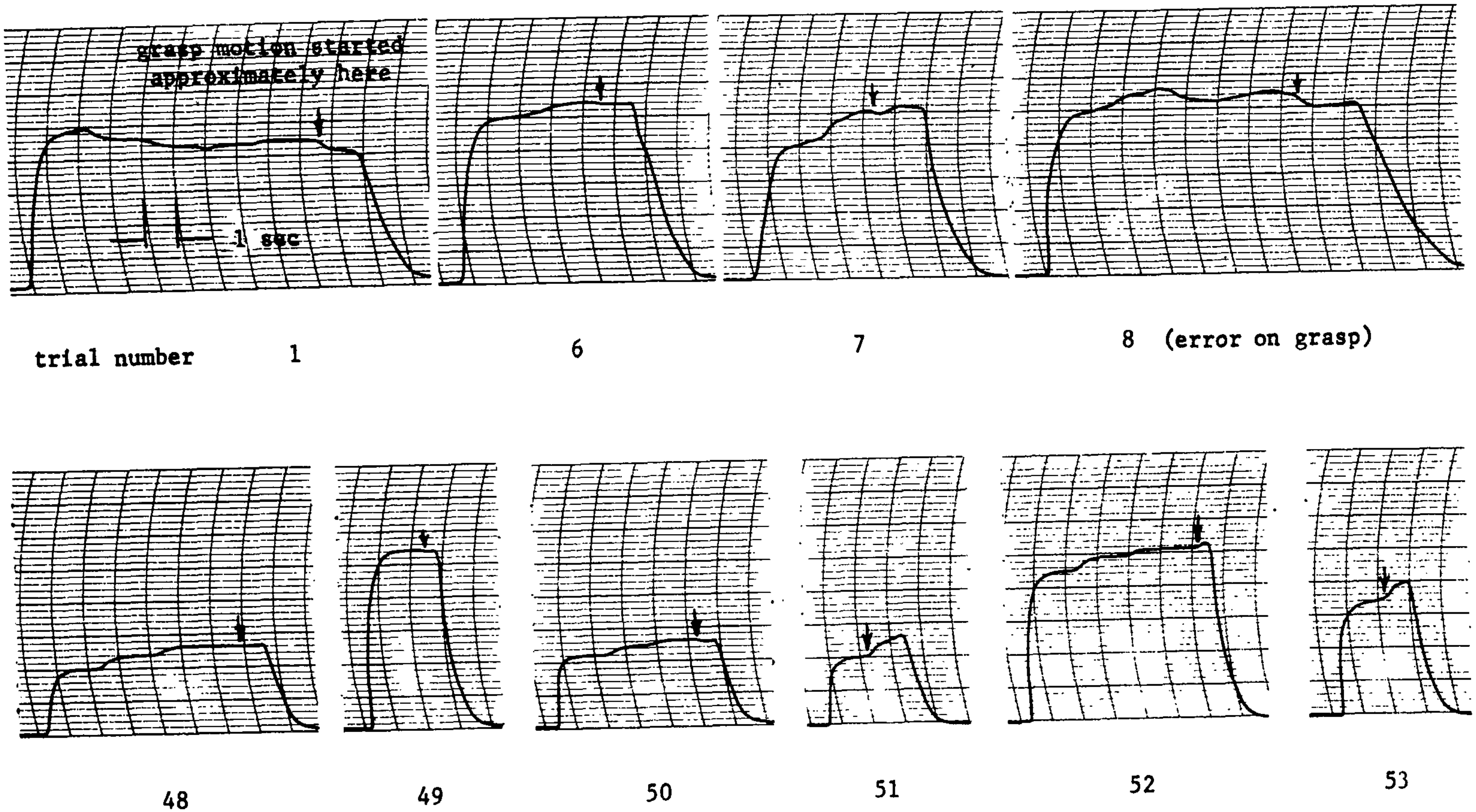
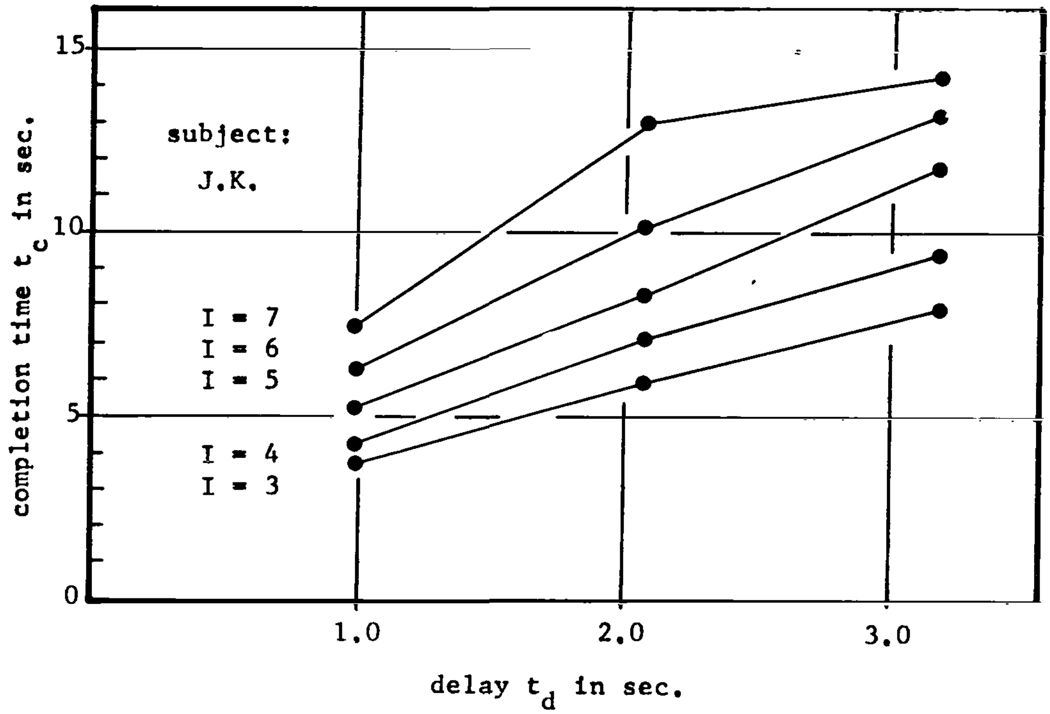



Fig. 4.7. Typical Records of Transverse Positioning Movements for Subject E.C. on First Delay Session (various distance-tolerance combinations)



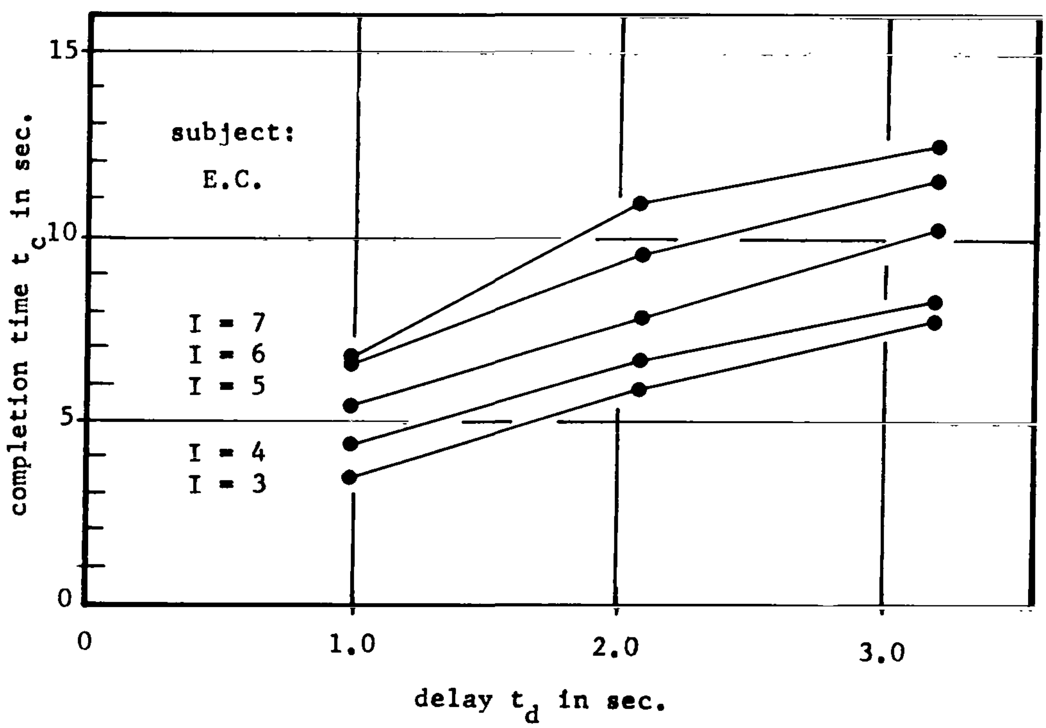




Fig. 4.8. Completion Time as a Function of Delay, Experiment I

improved his times in the delayed conditions relative to the stable performance of J.K. This supposition is strengthened when, in a later section, the numbers of times the subjects stopped and waited for feedback is considered.

Figure 4.8 shows the relation between completion time and delay for the two subjects. It can be seen that delay had generally a linear effect on the times at each level of difficulty.

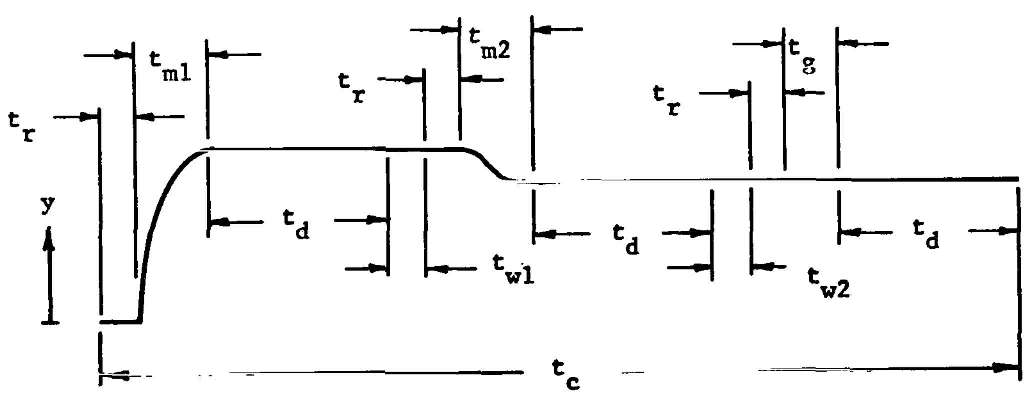
In conclusion, this experiment showed that, for a simple positioning task, remote manipulation under the direct control of an operator can be successfully performed even with a substantial delay. Both operators adopted a simple strategy of making a series of open-loop moves, with a wait of a delay time after each to obtain correct visual feedback. An increase in the difficulty of the task was compensated for by an increase in the time used to perform it. Thus, time can be traded to get accuracy even with a delay.

## 4.4. Predicting Completion Time for Simple Tasks

### 4.41. Analysis of the Simple Task

In order to understand properly the way in which the move-and-wait strategy is used by an operator to perform remote manipulation with a delay, one must examine the sequence of positioning movements in detail.

A typical pattern of operator movement from the experiment reported in the previous section is shown in Fig. 4.9. Following the command to start, there




m = 2

Fig. 4.9. Typical Pattern of Positioning Movements

is a reaction time delay $t_r$; then the operator makes his initial open-loop movement, taking a time $t_{m1}$, and waits a delay time $t_d$ until the remote hand responds. A slight additional pause was usual at this point before the next corrective movement began. It is assumed that this pause includes the reaction time $t_r$ associated with the succeeding move. Any remainder is denoted as waiting time, $t_{w1}$. After the final movement and wait, the subject performs a grasping motion, requiring a short time $t_g$ and there is a final period $t_d$ before the remote fingers begin to close. Grasping time could not be obtained from the recorded data alone.

If m denotes the number of times the operator waits for a delay period to get correct feedback, and $t_c$ is the completion time, and $t_r$ is assumed constant, then

$$t_c = (m + 1)(t_r + t_d) + \sum_{i=1}^{m} (t_{mi} + t_{wi}) + t_g \qquad (4.1)$$

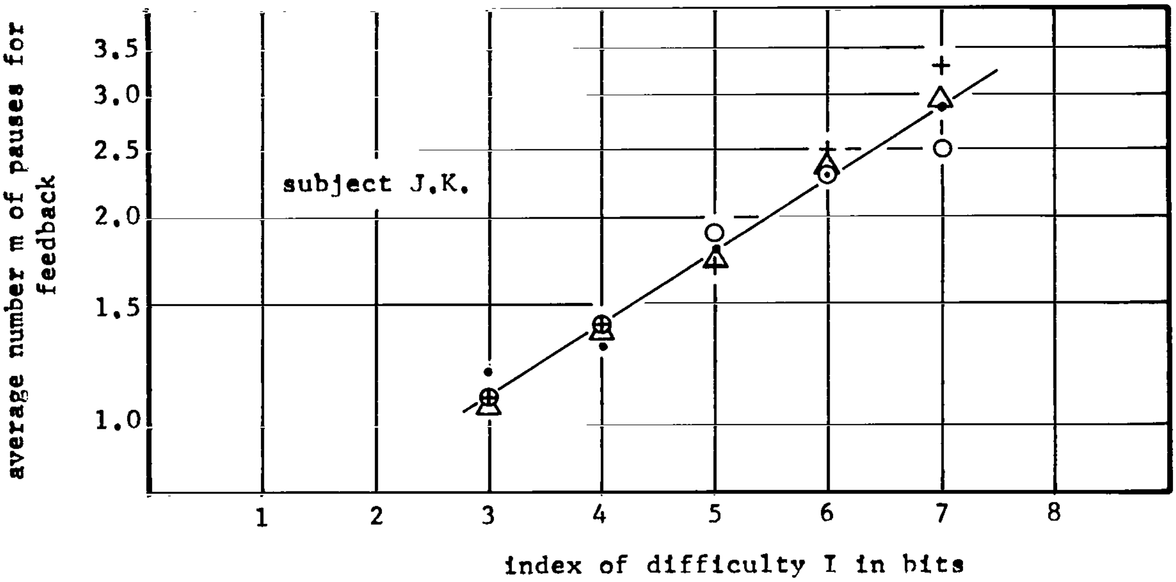
4.42. Effect of Length of Delay on the Number of Pauses for Feedback and the Movement Time

If it be true that both m and the times $(t_{mi} + t_{wi})$ and $t_g$ are independent of delay, then it should be possible to predict the completion time by use of an equation similar to Eq. (4.1) and measures of m and the time to move which can be got in the no-delay condition.

The number of moves followed by a wait of one delay time, m, was counted from the recorded positioning movements of the simple manipulation experiment. The average value of m as a function of task information and delay is shown in Fig. 4.10 for both subjects in Experiment I, J.K. and E.C. The graph for J.K. shows that m was essentially independent of delay. E.C.'s data, however, shows a progressive decrease in the average with delay. This can be attributed to the fact, mentioned earlier, that practice and delay time were confounded and that E.C. had not had prior experience.

The other quantity which must be estimated in order to predict completion times is a measure of the time required for the movements. In order to show the effect of delay on the total movement time,

$$\sum_{i=1}^{m} (t_{mi} + t_{wi}) + t_g,$$



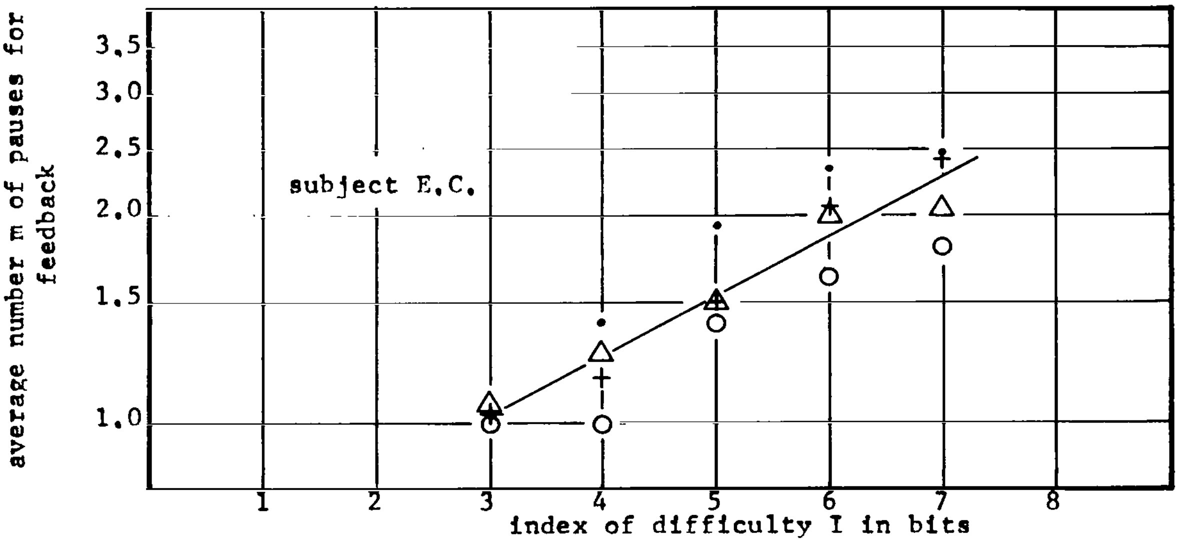




Fig. 4.10. Number of Times Feedback was obtained as a Function of Task Difficulty, Experiment I (• m 1.0 sec. delay, + m 2.1 sec. delay, O m 3.2 sec. delay; Δ N)

Fig. 4.11 gives the derived movement time $t_c - (m + 1)(t_r + t_d)$ as a function of delay and task information. The experimental averages are $t_c$ and m and $t_r$ is the subject's average initial reaction time from the no-delay case. It can be seen from the graph that this quantity which approximates the total movement time shows some effect that might be attributable to delay in the case of J.K. However, it is neither very large nor is it monatonic with delay. There is no consistent delay effect for E.C.

It would appear, then, from the experimental data, that when the move-and-wait strategy is consistently used, the number of pauses for feedback and the time to make the open-loop moves are both largely insensitive to delay. Thus the primary effect of the amount of delay is on the length of pause necessary to get correct feedback.

### 4.43. Estimating the Number of Pauses and the Movement Time

An estimate of the number of times an operator will require correct feedback to perform a given task when there is a delay can be got in the no-delay case by making him adopt a strategy requiring discrete open-loop moves. This can be done by having him perform the task in question on the manipulator with the restriction that all movements must be made with the eyes shut, but that the eyes may be opened for as long as desired between movements. Turning the room light on and off would be an alternative to opening and closing the eyes. The operator is instructed to perform the task opening his eyes as seldom as possible, and the number of times he does so N is recorded. Just such a test was administered to both of the subjects in the experiment reported in the previous section. J.K.'s test was given following the final session with delay, and consisted of 30 trials at the 6-inch distance for each of the values of task difficulty, taken in random order. E.C. was tested between the 2.1 and 3.2 sec. delay sessions with each of the 15 distance tolerance combinations presented 10 times in random order, just as for the delay case.

Figure 4.10 shows the average value of N along with the average number of pauses m used in the delayed cases as a function of difficulty, I. It can be seen from the figure that for J.K., N(I) is almost precisely the same as m(I). For E.C. the values of N are almost the same as the average of the values for m at the two delay conditions, one which preceded and one which followed the test for N. This is consistent with the assumptions that the m values for E.C. differ because of learning and that N and m are measures of much the same thing.

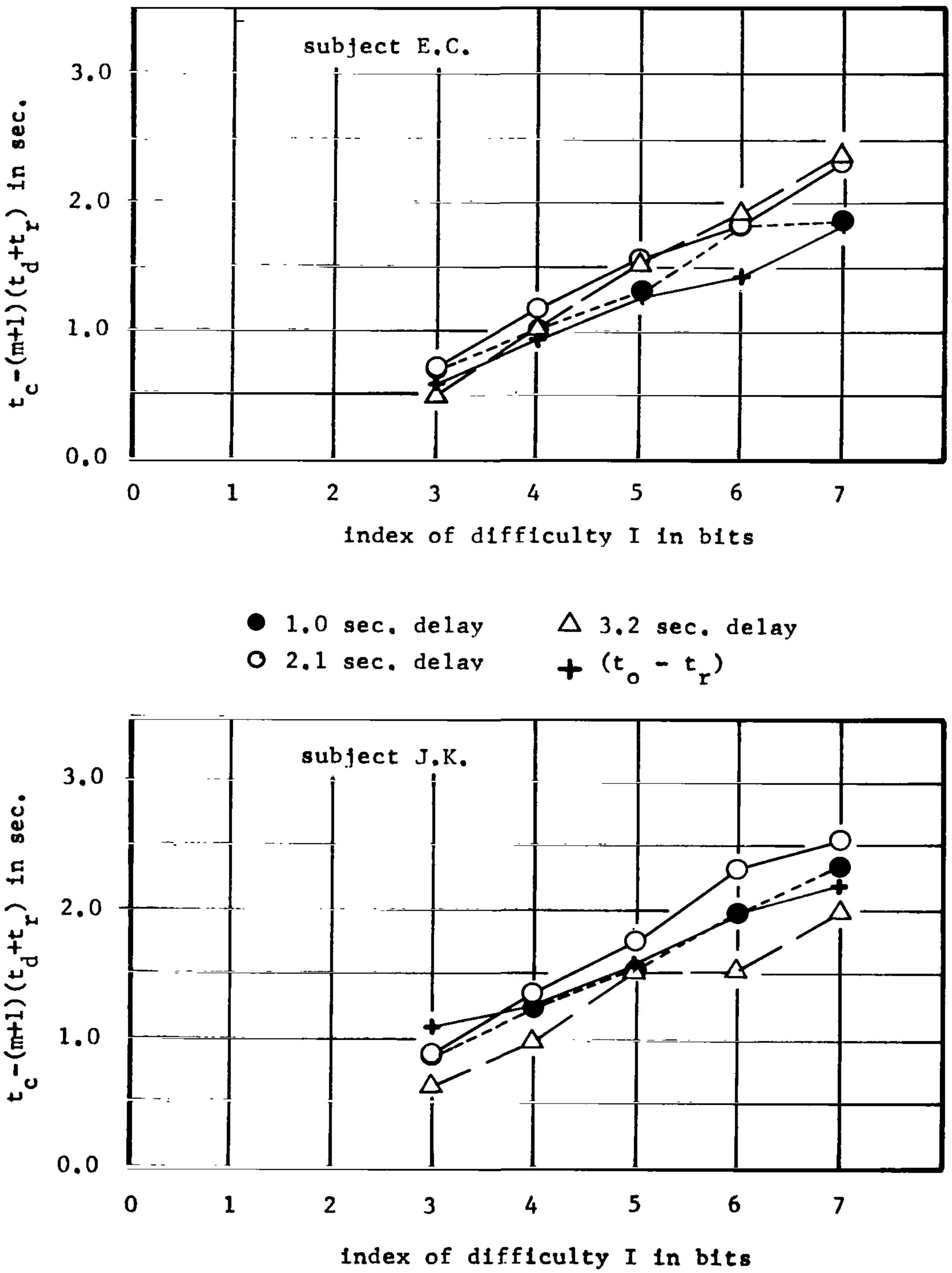



Fig. 4.11. Derived Movement Times as a Function of Task Difficulty I, Experiment I

For estimating the total movement time there are two possibilities.

1. The time required to perform the task in the zero delay case, $t_o(I)$ includes the initial reaction time, $t_r$ and a grasping time, $t_g$. Moreover, $t_o(I)$ must also include time to make the necessary positioning movements, assess their effect, and correct them to achieve the final accuracy--time components qualitatively like the times $t_{mi}$ and $t_{wi}$. This leads to the assumption that, as a first approximation, $t_o(I)$ will be equal to the portion of the completion time not attributable strictly to the delay.

$$t_o(I) \approx t_r + \sum_{i=1}^{m(I)} (t_{mi} + t_{wi}) + t_g \tag{4.2}$$

Actually one would expect $t_o(I)$ to be somewhat of an underestimate since it is obtained with continuous movement. Starting and stopping presumably require additional amounts of time.

In Fig. 4.11, $(t_o - t_r)$ is shown for comparison with the times $t_c - (m + 1)(t_r + t_d)$, of which it would be an estimate. It is seen to be somewhat low in E.C.'s case but approximately correct in that of J.K.

2. The second measure for estimating the movement time is the time $t_N$ required to perform the task open-loop on the test for N. This time includes all the reaction times as well as the movement times. Thus, as an approximation,

$$t_N(I) \approx t_r + \sum_{i=1}^{m(I)} (t_r + t_{mi} + t_{wi}) + t_g \tag{4.3}$$

This approximation would be expected to be somewhat high since it includes the times required for closing, opening and focusing the eyes. Moreover, if $t_N$ is to be used to estimate the movement time, it should be obtained under conditions in which the operator is trying <u>both</u> to work rapidly and to use as few looks for feedback as possible, otherwise the operator may sacrifice time to try to get a better score on moves, or the other way around.

For J.K., $t_N(I)$ was not obtained. It was recorded for E.C., but without his even being aware of being timed and with only the instruction to use as few moves as possible. As would be anticipated in such a case, $t_N$ is much higher than $t_c - (m + 1)t_d$, of which it would be an estimate.

4.44. Predicting Completion Time with Delay

If the two estimates of the movement time are each combined with the estimate of the number of waits for feedback N two equations are obtained for predicting completion time with delay when the move-and-wait strategy is used:

$$t_{c1}(I) = t_o(I) + N(I)(t_r + t_d) + t_d \tag{4.4}$$

where $t_{c1}$ is the prediction of $t_c$ using $t_o$, and

$$t_{c2}(I) = t_N(I) + [N(I) + 1]t_d \tag{4.5}$$

where $t_{c2}$ is the prediction of $t_c$ using $t_N$.

Equation (4.4) is similar in form to the equation proposed by Lee[7] for the time required to speak without stuttering when auditory feedback is delayed. Lee's formula is

$$T = t + nd \tag{4.6}$$

where T is the total time, n the number of phonemes and spaces, t the average time with no delay and d the delay time. In effect, n is an estimate of the number of pauses for feedback, hence the equation may be written, using the notation of this study, as

$$t_c = t_o + Nt_d \tag{4.7}$$

Since the speaker already knows what he is going to say, the feedback indication merely acts as a trigger for the next, already anticipated, sound. Thus, since there is no decision to be made, no reaction time need be included. Moreover, the output is the person's speech, not the delayed transcription, so there is no terminal delay. Except for the reaction times and final delay, the prediction Eq. (4.4) and Lee's Eq. (4.7) are the same.

Figures 4.12 and 4.13 show $t_{c1}(I)$ from Eq. (4.4) compared with the measured times for the two subjects, J.K. and E.C. All the measures for computing the predicted times were obtained by using the manipulator with no delay. It can be seen that a fairly accurate fit to the data of each subject is obtained.

4.45. Confirmatory Experiment (Experiment II)

Objectives:

An experiment was designed, with the following objectives:

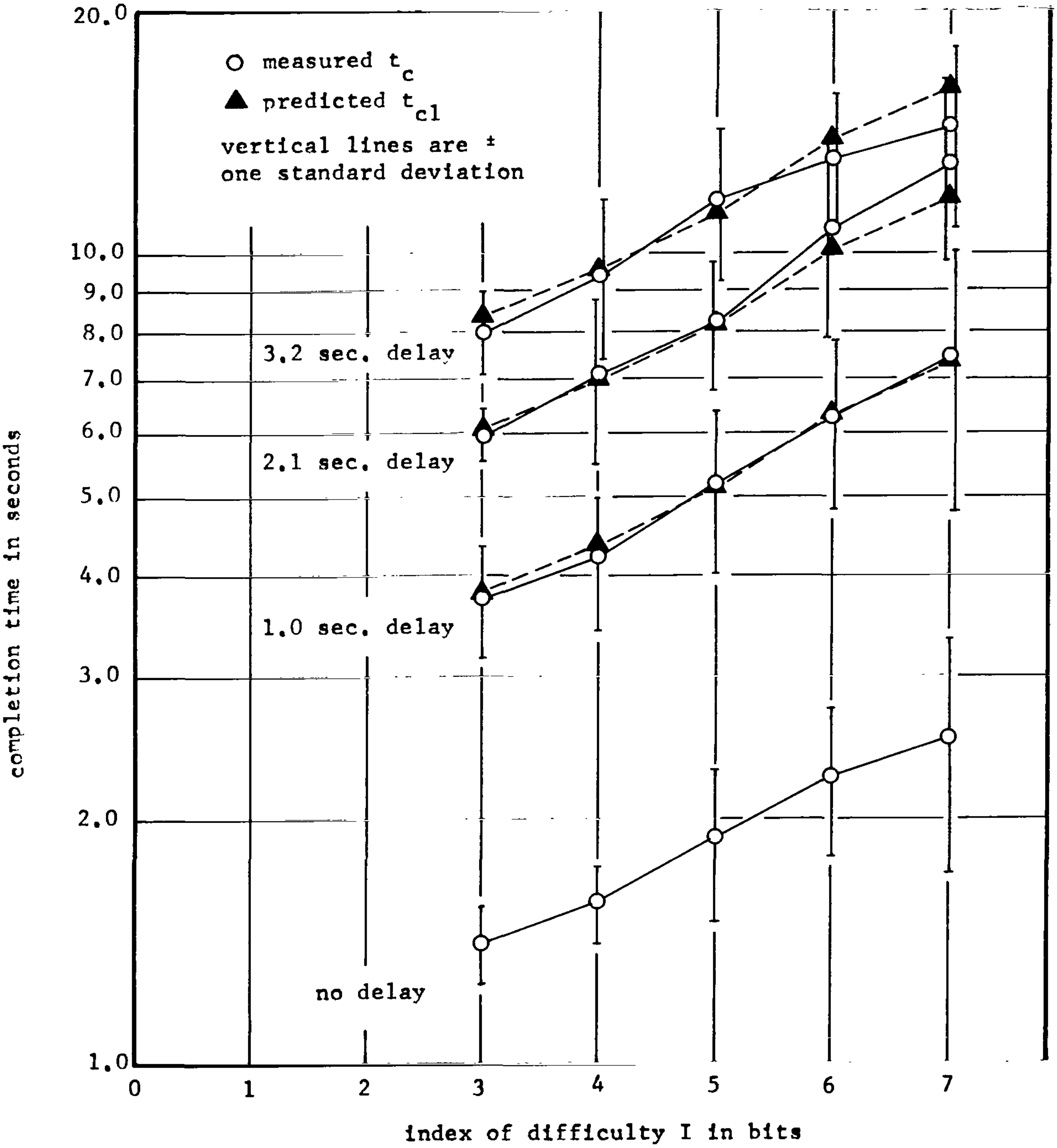



Fig. 4.12. Measured and Predicted Completion Times for Subject J.K., Experiment I

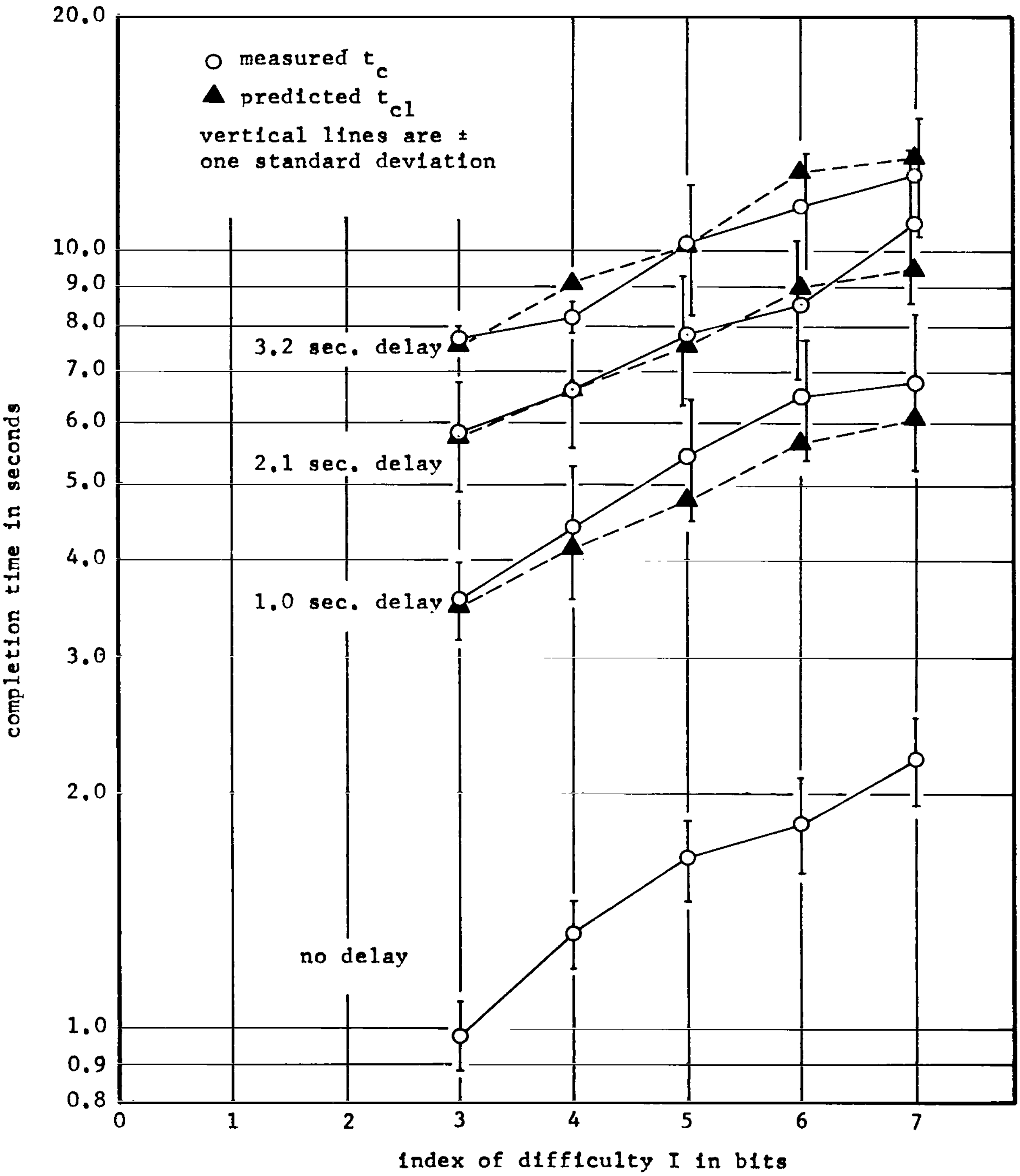



Fig. 4.13. Measured and Predicted Completion Times for Subject E.C., Experiment I

1. To further determine whether operators would tend to discover and adopt the move-and-wait strategy when a delay is present.

2. To test the accuracy of the methods for predicting completion time with delay.

3. To further examine the effects of task information and delay on completion time.

Experiment:

The experimental task was the simple one of positioning the remote hand and grasping a block, as previously described. There were seven paid student subjects, each operating with one delay--three subjects at a delay of 1.0 sec., two at 2.1 sec., and two at 3.2 sec. Since the first experiment showed that movement distance was not a significant variable, a single distance of 6 inches was used. Block size was varied to give five levels of difficulty; I = 3,4,5,6, and 7, as before. An error was scored if the block was moved before being grasped, and the trial repeated. At each of the conditions enumerated below, the I values were presented in random order for a total of 10 correct trials at each level of difficulty.

Each subject had a practice session on the first day, and a test session on the following day. For practice, the following conditions were taken in order:

1) no delay

2) delay

3) open-loop (eyes closed while moving)

None of the subjects was prompted in any way beforehand on how to cope with the delay. Hence the first session provided an opportunity to determine what strategy would be adopted. The open-loop condition was taken last to avoid suggesting a strategy to the subjects.

The test session consisted of the same task performed under the following conditions in order:

1) no delay

2) open-loop (N1)

3) delay

4) open-loop (N2)

Before the delay condition on the test session, subjects were instructed to use the move-and-wait technique. There was a 10-minute rest period between conditions on both sessions.

Results:

Six of the seven subjects spontaneously adopted the move-and-wait strategy on the first session, and when asked afterward how they coped with the delay each described the strategy sufficiently well to make it clear that it was consciously evolved and applied. The other subject could not describe what he had done other than to say he had "adapted" to the delay. He had, in fact, used a combination of moving slowly with an occasional wait for feedback. His times were somewhat greater than those of the other two subjects at the same delay, 1.0 sec. Since his strategy was not consistent on the test session even after he was instructed to move and wait, his results are not included.

Figures 4.14 through 4.19 show completion time as a function of task difficulty for delay and no delay for the six subjects using the move-and-wait strategy. Completion time with and without delay appears to have approximately the same relation to the index of difficulty as was found in the first experiment. Figure 4.20 is a graph of average, completion time vs. delay, for each level of difficulty, and, as in Experiment I, the relation is linear in each case.

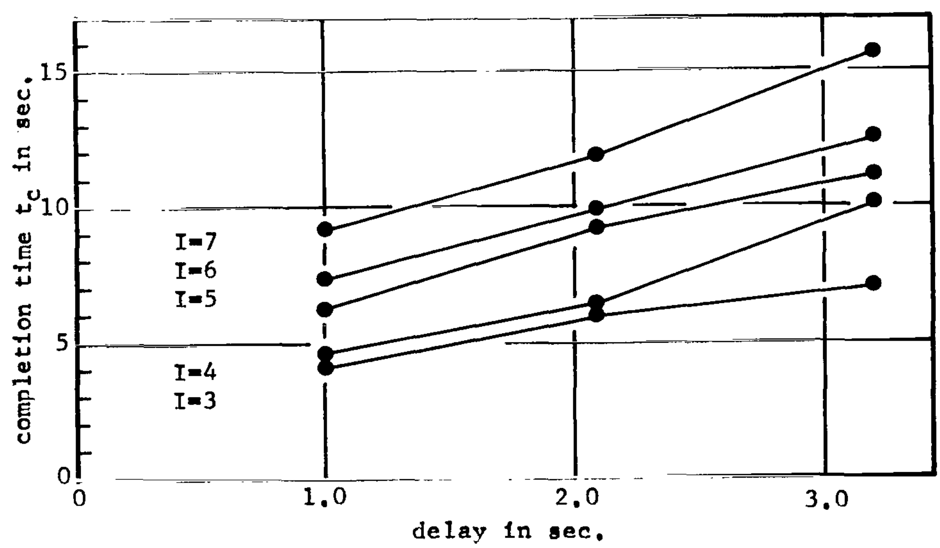



Fig. 4.20. Completion Time as a Function of Delay, Experiment II

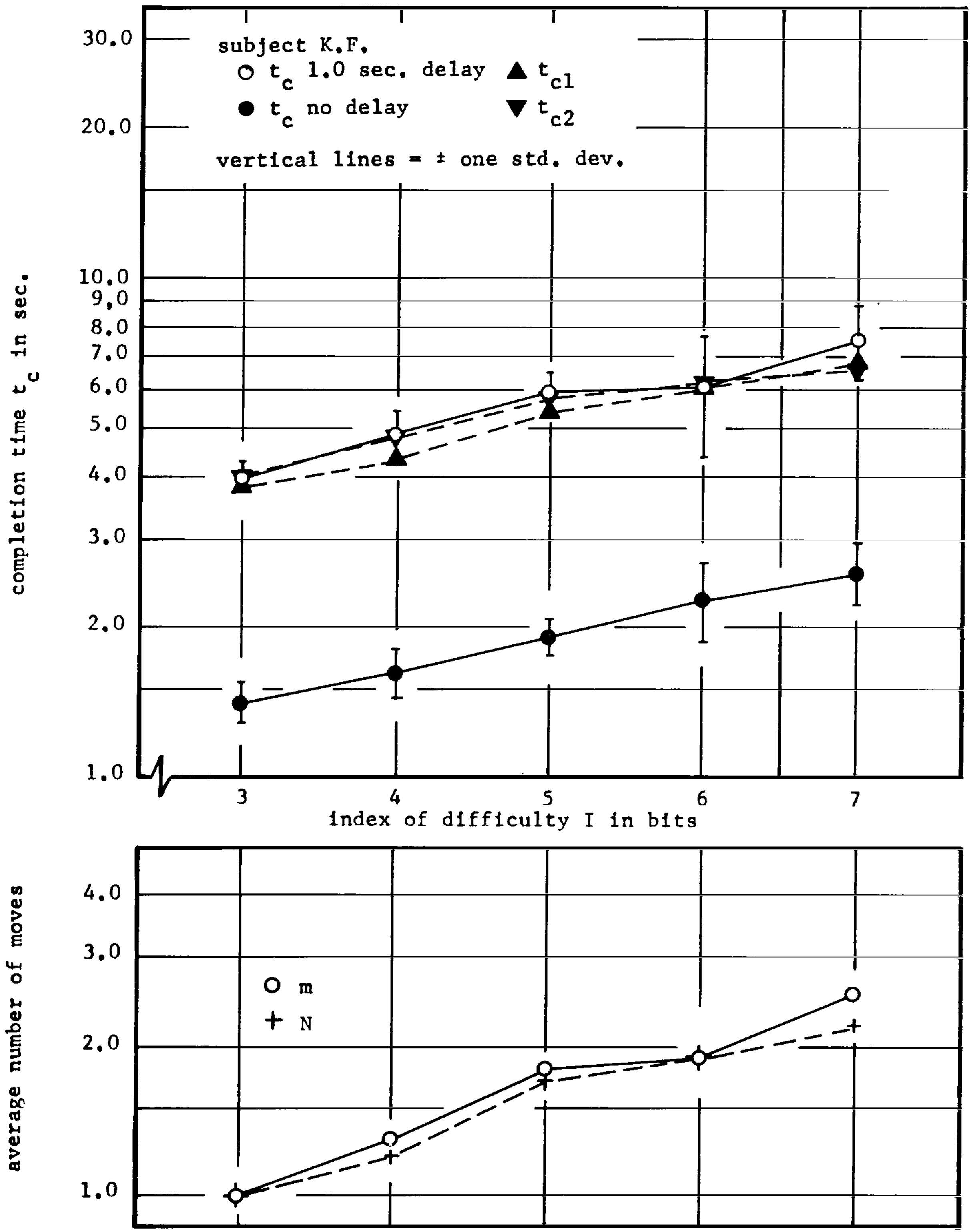



Fig. 4.14. Results from Experiment II, Subject K.F.

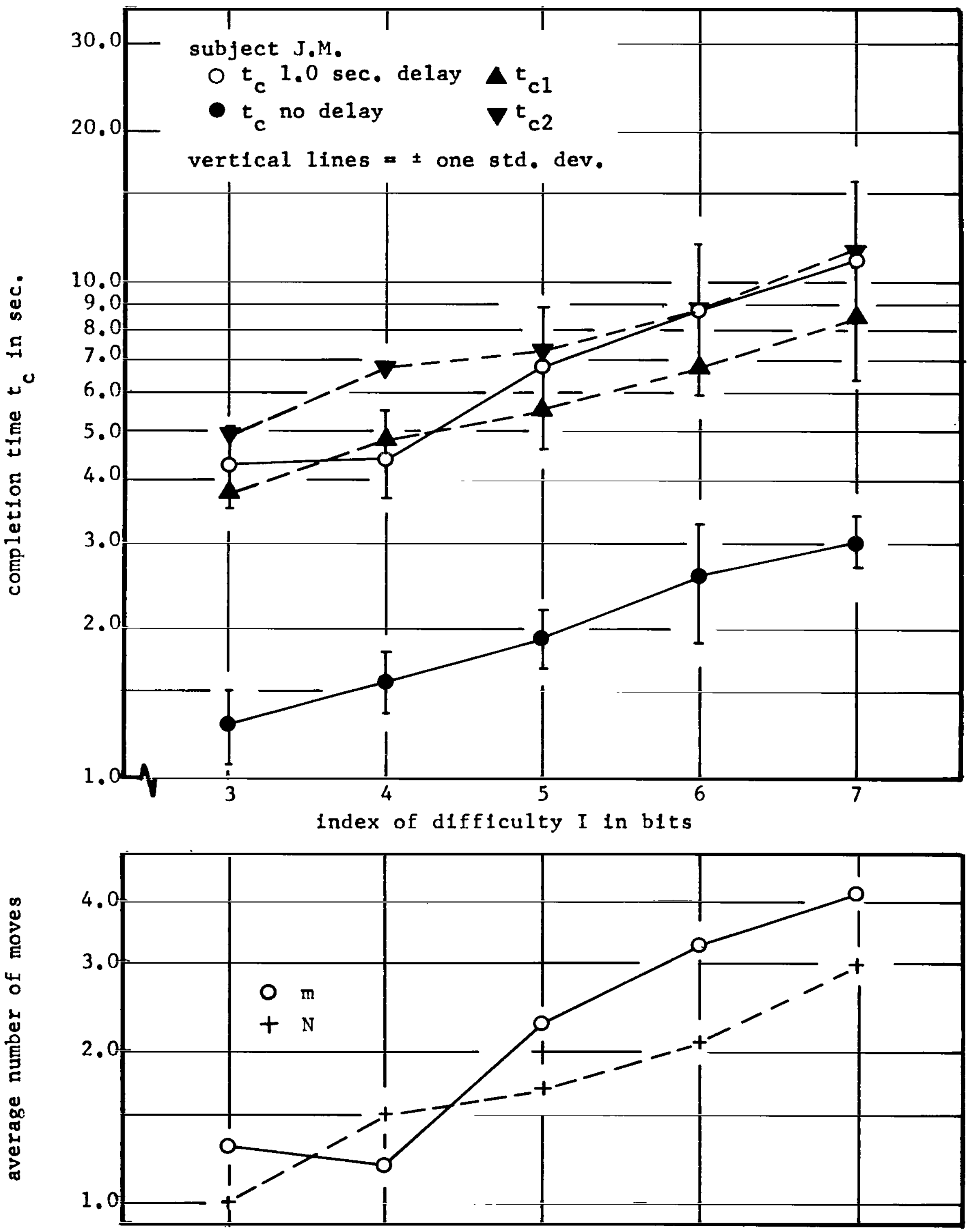



Fig. 4.15. Results from Experiment II, Subject J.M.

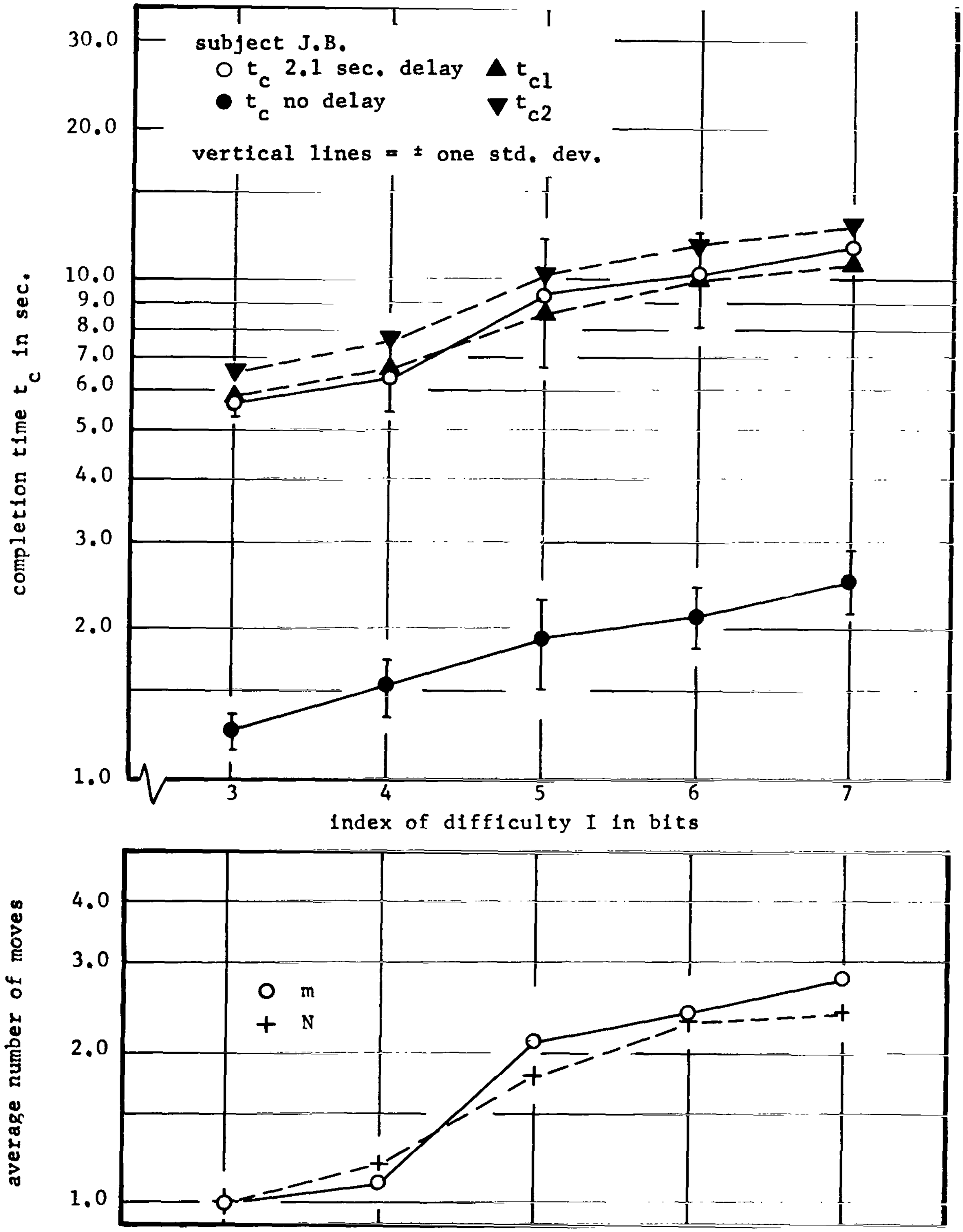



Fig. 4.16. Results from Experiment II, Subject J.B.

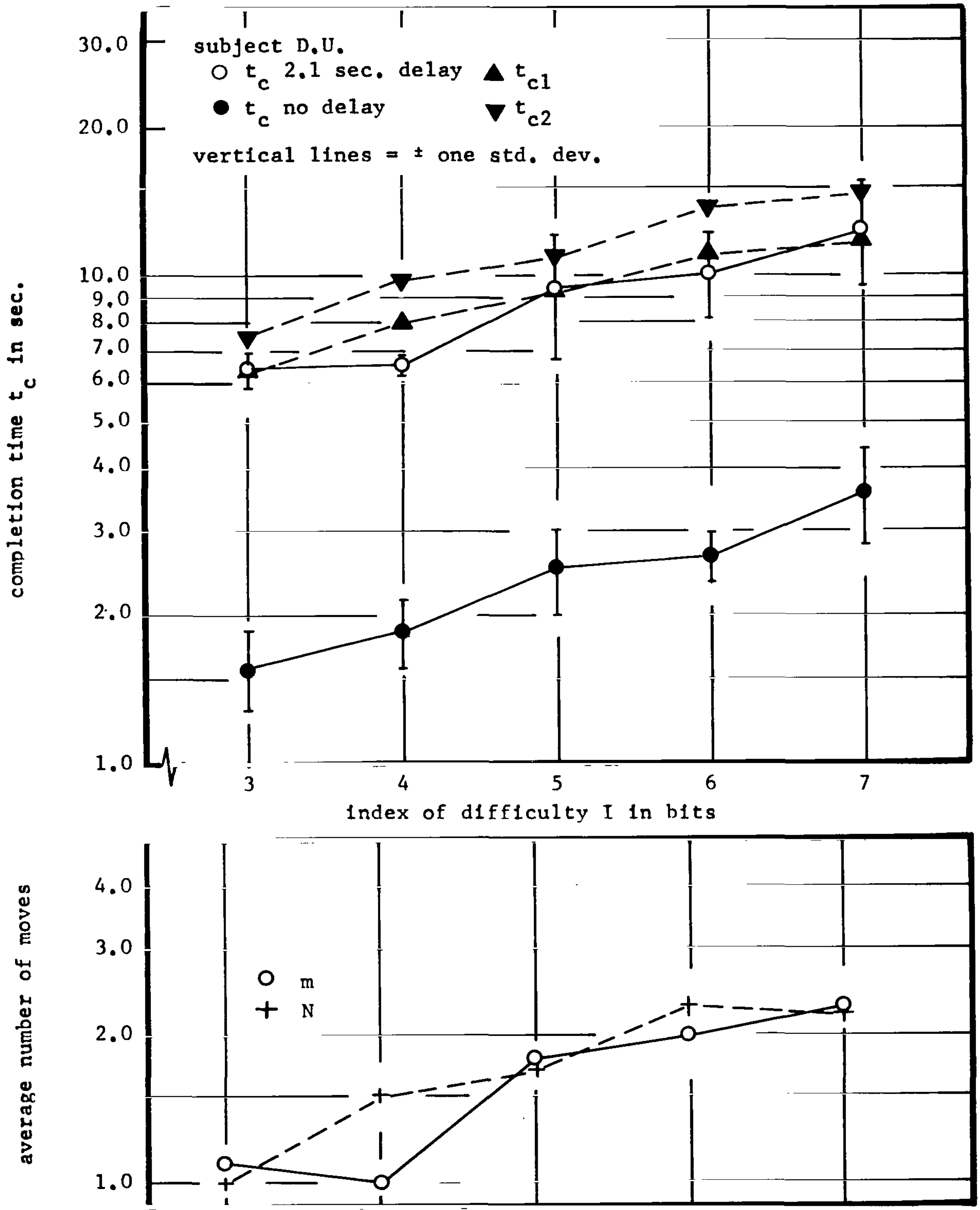



Fig. 4.17. Results from Experiment II, Subject D.U.

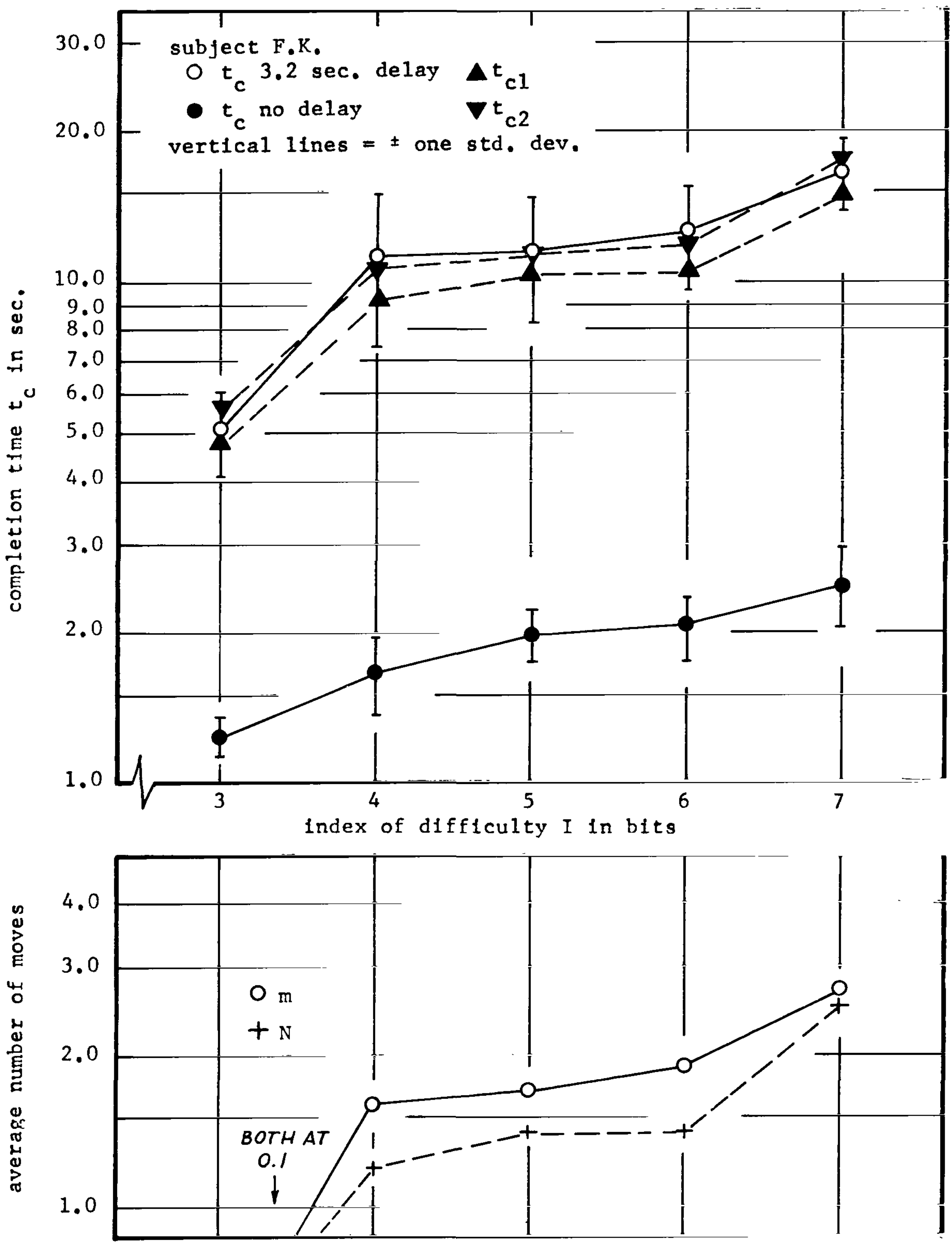



Fig. 4.18. Results from Experiment II, Subject F.K.

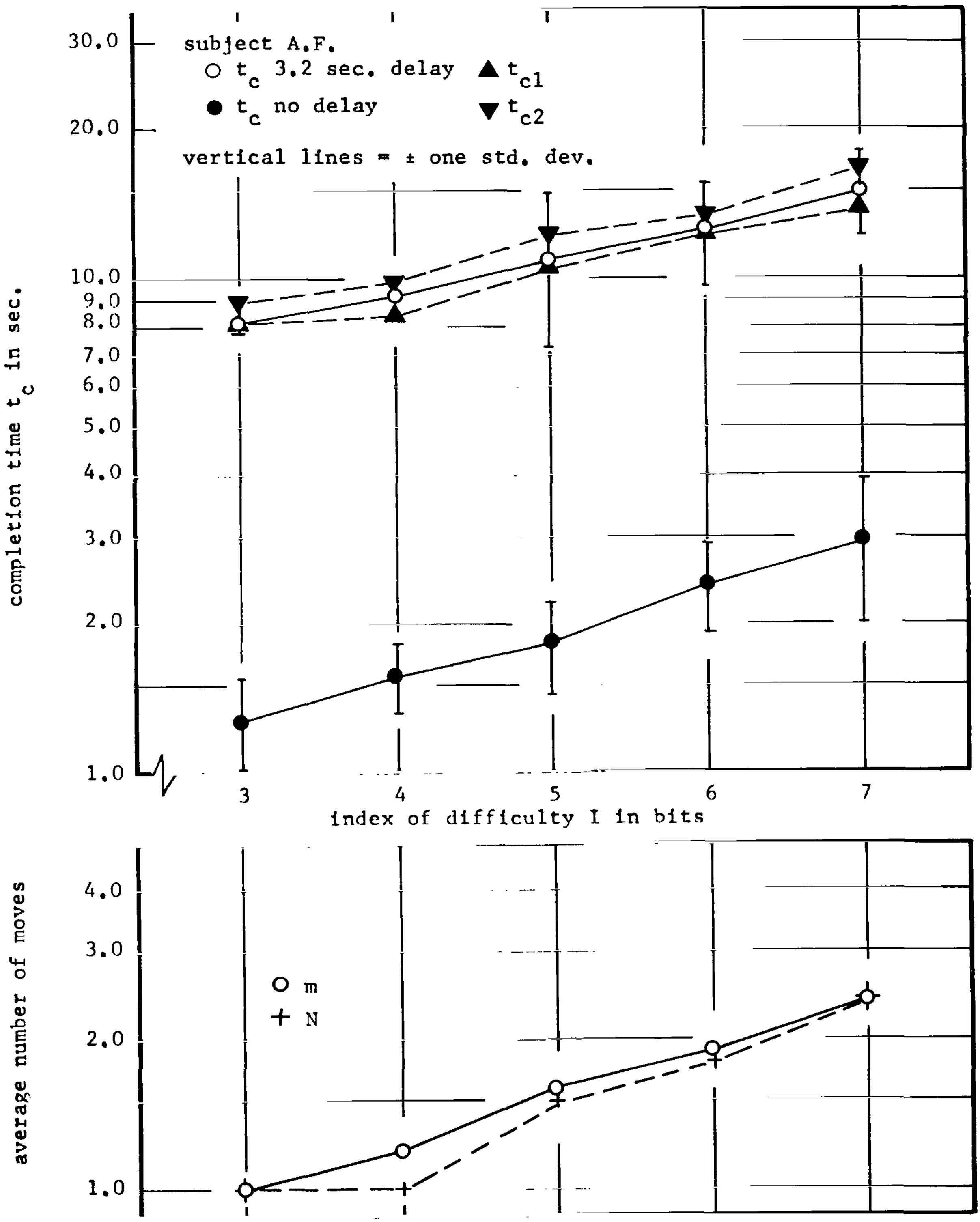



Fig. 4.19. Results from Experiment II, Subject A.F.

Also shown in the figures are the average number m of pauses for feedback counted from the recorded data and the average number of times feedback was got in the first open-loop test N1. The results from the second open-loop test N2 were consistently lower, and since the subjects had so little training, this is attributable to practice. Since N1 corresponds to the same amount of practice as does the delay condition, N2 was not used. N does, indeed, appear to estimate m with considerable accuracy.

Predicted times were calculated from Eq. (4.4) of the previous section,

$$t_{c1}(I) = t_o(I) + N(I)(t_r + t_d) + t_d$$

in which

$t_o(I)$ = completion time, no delay

$t_d$ = delay time

$t_r$ = reaction time (the initial reaction time from the no delay condition was used)

$N(I)$ = the average number of times feedback was used in the first open-loop test

The calculated values are also shown in Fig. 4.14 through 4.19.

On the open-loop test the subjects were timed, starting on the word "go" just as in the other conditions. Although they were only instructed to open their eyes as few times as they could, they were aware of being timed. Thus, although the relative importance of time was not controlled, it was thought possible to use the time $t_N$ in the first open-loop condition to give some indication of the efficacy of the second prediction equation. Accordingly, calculations were made from the equation

$$t_{c2}(I) = t_N(I) + [N(I) + 1]t_d$$

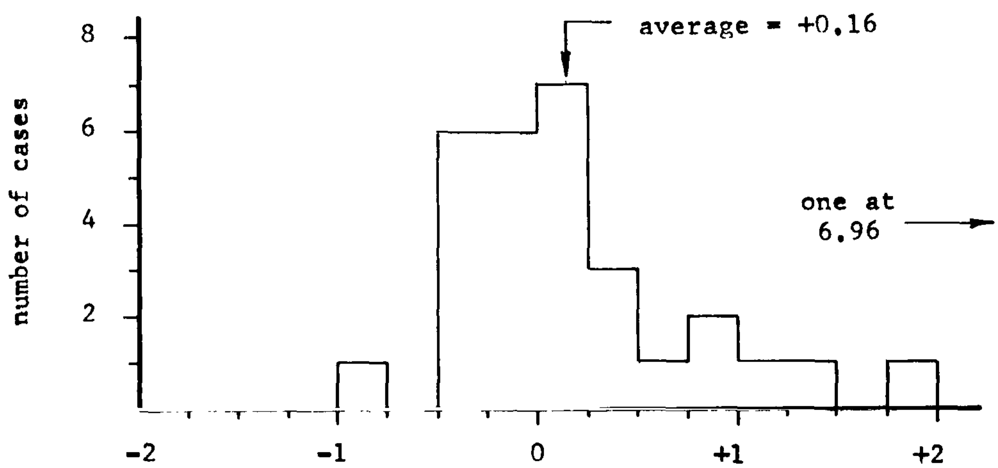
and these predicted times are also shown on the graphs.

As was anticipated, the predictions $t_{c1}$ based on $t_o$ generally underestimate the average measured time $t_c$, and the predictions $t_{c2}(I)$ based on $t_N$ generally overestimate it. This suggests that the two predictions be averaged to give a new estimate $t_{ca}(I)$ of the completion time with delay.

Table 4.1 gives the means and standard deviations of the errors of

| prediction error | mean | standard deviation |
| --- | --- | --- |
| $\frac{t_{c1} - t_c}{\sigma_{data}}$ | -0.30 | 0.40 |
| $\frac{t_{c2} - t_c}{\sigma_{data}}$ | +0.63 | 0.85 |
| $\frac{t_{ca} - t_c}{\sigma_{data}}$ | +0.16 | 0.60 |

Table 4.1. Errors of Prediction in Units of the Standard Deviation of the Data, Experiment II




$\frac{t_{ca} - t_c}{\sigma_{data}}$ in increments of 0.25

Fig. 4.21. Histogram of Prediction Error Frequencies, Experiment II

prediction in units of the standard deviation of the ten measured times the average of which is predicted. In addition, Fig. 4.21 shows a histogram of the distribution of the error term $(t_{ca} - t_c)/\sigma_{data}$. The entries in the table were calculated from the pooled set of results for the six subjects. The one anomalous case, shown in the histogram of Fig. 4.21, I = 4 for subject D.V., was excluded. Thus each entry represents 29 error terms.

As Table 4.1 shows, the prediction $t_{ca}$ is very good. On the average, $(t_{ca} - t_c)/\sigma_{data}$ is only +0.16, which a student's t test reveals to be not significantly different from 0.0 at the 5 per cent level. The standard deviation of this error term is only 0.60 with a 90 per cent upper confidence limit of 1.13. Hence, each prediction $t_{ca}$ based on ten trials to measure $t_o$ and ten trials to measure N and $t_N$ is at least as good an estimate of $t_c$ as one actual trial with delay, and more likely almost as good as three.

Errors, trials on which the block was moved prior to being grasped, followed much the same pattern as in Experiment I. In all, excluding the second open-loop condition, 13.1 per cent of the trials were in error. Just half the errors were scored on the delay condition, with the rest almost equally divided between the no delay and open-loop conditions. A student's t test indicated that the difference in errors between the delay and open-loop conditions was significant at the 1 per cent level. As in the previous experiment, errors were more frequent at the higher levels of difficulty, the highest, I = 7, accounting for more than half. And again, an error on a trial was much more likely if there had been one on the preceding trial.

## 4.5. Completion Time as a Function of Delay for a Complex Task (Experiment III)

### 4.51. Objectives

Tasks of greater complexity than positioning and grasping can, in principle, be reduced to components whose difficulty can be expressed in information units[25]. However, the results from the simple task experiments cannot be simply extended to complex tasks for several reasons.

1. Manipulative actions are seldom precisely the same each time a task is done, but vary in response to contingent events.

2. It has not been established whether quite different tasks with the same information content require the same time.

3. Parts of a task do not always contribute independently to the total completion time[23].

For these reasons, it was deemed necessary to investigate the performance of a more complicated delayed manipulation task. The objectives of the experiment were:

1. To determine whether the move-and-wait strategy would be successful and could be consistently maintained for a complex task.

2. To compare the effect of delay on a complex task with that on the simple task.

3. To determine whether the completion time could be predicted for a complex task in the same way and with the same accuracy as it was for the simple task.

4.52. <u>The Experiment</u>

The experimental task is diagramed in Fig. 4.22. The operations, in sequence, are:

1. Two clocks, one for completion time and one for reaction time, are started, and simultaneously a light flashes telling the operator, O, to begin. O moves the manipulator from its starting position and grasps an object called tool 1. The initial movement of the master hand stops the reaction time clock.

2. O inserts tool 1 into an opening in a block, pushing out tool 2. O then releases tool 1, moves the manipulator hand counter clockwise around the block, and grasps tool 2.

3. O extracts tool 2, releases it, and then pushes on one side of it to rotate it counter clockwise by $90^{\circ}$.

4. O grasps tool 2 again, by a protrusion on its side, moves it around to the right side of the block and slides its beveled left end under the lever of a micro-switch, stopping the completion time clock and ending the task.

The task is not difficult (it has been done in less than 6 sec. with no delay) yet it incorporates a number of features common to many useful manipulations: grasping and releasing objects, positioning objects with respect to

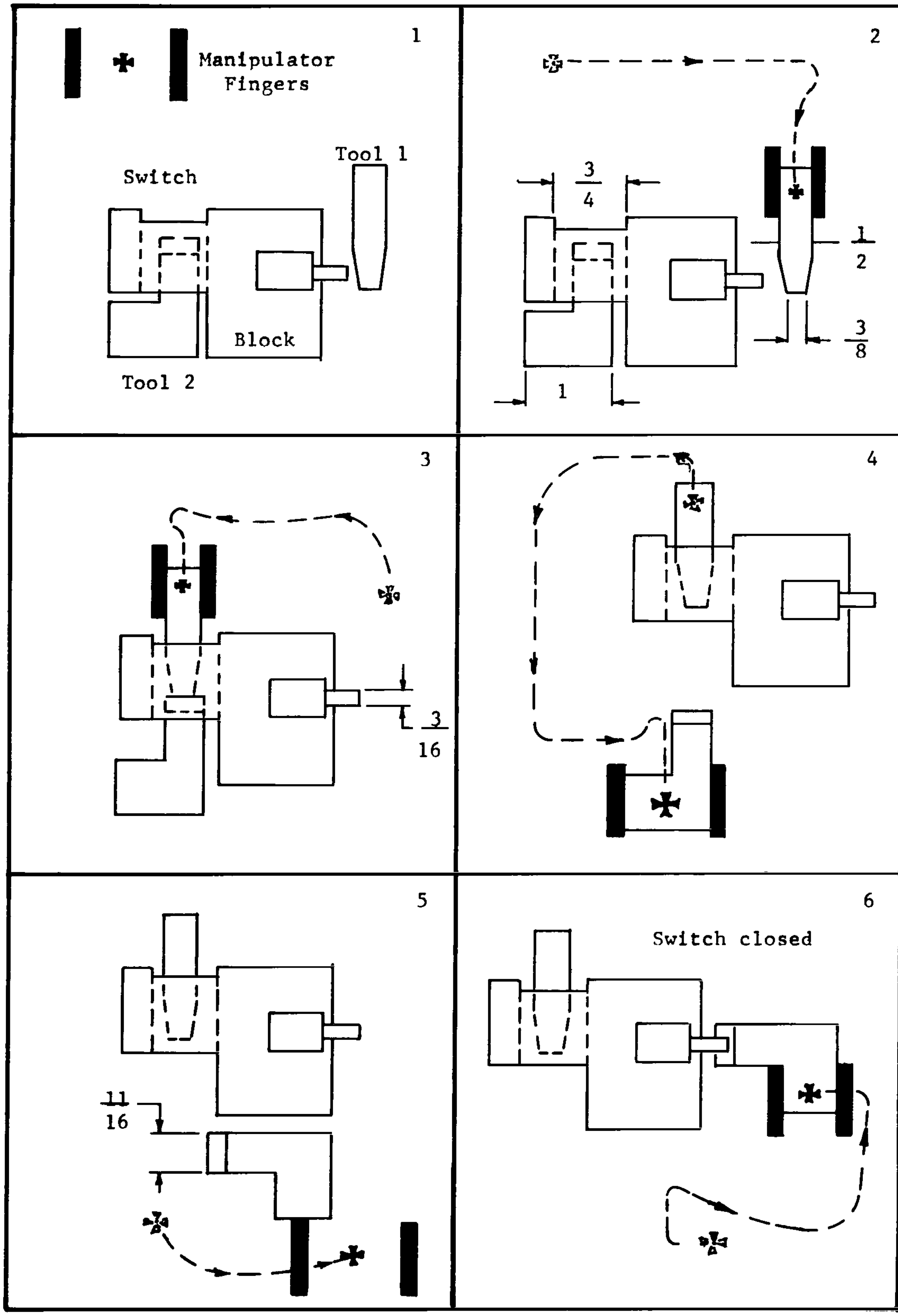



Fig. 4.22. Diagram of Task of Experiment III

others, transporting objects, moving the hand to avoid disturbing the arrangement of the task, etc.

An error was scored for a trial of the task on which any one of the following occurred.

1. Tool 1 was moved before being grasped.
2. The block was accidentally rotated by $20^{\circ}$ or more.
3. The objects were disarranged so that the task could not be completed.
4. The objects were disarranged in such a way that, in the judgment of the experimenter, the task was essentially changed, e.g. if tool 2 were rotated clockwise instead of counter clockwise completely changing the sequence of operations needed to grasp it.

The latter two categories of error were by far the least frequent.

The subjects were 4 male students. There were four practice and four test sessions, each lasting about one hour and on separate days. On each session, the subjects performed enough trials to do the task 10 times correctly at each of the three following conditions:

1. no delay (denoted by o)
2. open-loop (N)
3. delay (D)

Four delays were used, 0.3, 1.0, 2.1, and 3.2 seconds, and on all sessions subjects were instructed to use the move-and-wait strategy with delay.

On the open-loop condition, the subjects wore headphones that presented an approximately white noise to prevent their making use of any auditory cues from the remote task.

During practice, the delays were taken in the order, 2.1, 1.0, 0.3, and 3.2, and the order of conditions on each session was O, N, D. For the test, the subjects, taken at random, were assigned delay times and orders of conditions according to Table 4.2 below. The numerical entry is the delay and the arrangement of O, N and D gives the order of the conditions.

Test Session

| Subject | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| | M.M. | 0.3 OND | 1.0 OND | 2.1 ODN | 3.2 NDO |
| | R.C. | 3.2 ODN | 0.3 NDO | 1.0 DNO | 2.1 OND |
| | R.J. | 2.1 DNO | 3.2 OND | 0.3 ODN | 1.0 NDO |
| | W.M. | 1.0 ODN | 2.0 NDO | 3.2 DNO | 0.3 OND |

Table 4.2. Order of Conditions for Experiment III

The reason for such assignment was to attempt to counterbalance for each delay time the effects of the number of preceding sessions and the number of preceding conditions in a session.

The performance measures that were recorded were:

1. The completion time with each condition, $t_o$, $t_N$, and $t_c$.
2. The number of times feedback was got by opening the eyes in the open-loop condition, N. (counted by the experimenter)
3. The initial reaction time, $t_r$. (Through an oversight, $t_r$ was recorded only for the delay case. However it was always clocked and observed in the case of no delay, and no difference was apparent.)
4. The number m of times a pause for feedback was made in the delay condition. (counted by the experimenter)

The number of waits with delay turned out to be very easy to count, even with the 0.3 sec. delay. Had there been any question about it, the tape recording could have been replayed, causing the slave to repeat its motions, and the pattern studied as often as necessary.

In an effort to induce the subjects to make a uniform and stable assessment of the relative importance of speed and accuracy, and to ensure high motivation, subjects could earn extra pay in proportion to the amount by which they bettered a criterion level of performance. The extra pay was docked in the same proportion for performance poorer than criterion, and it was also docked by a given amount for each error. Criteria were set for each of the performance measures.

There were no criteria for the first practice session. On the other practice sessions criteria were set for each of the performance measures. A criterion was a subject's median score or criterion from the previous session, whichever was lower. On all test sessions, criteria were the means from the final practice session plus 7.5 per cent. A completion time criterion at one delay was obtained from the criterion for another delay by use of completion times from two subjects in a preliminary experiment. The ratio of the criteria was made to equal the average ratio of the completion times.

Subjects did not know how the criteria were calculated, but they always knew the criteria and the pay rate, and were told their performance after each trial. During the test sessions, the extra pay rate was 2 cents for each 10 per cent of criterion for each trial and errors cost 10 cents. Subjects averaged 71 cents extra per session above the regular pay of $1.25.

4.53. Results

The completion times and predicted times for each subject are shown as a function of delay in Figs. 4.23 through 4.26. The averages over the four subjects are shown in Fig. 4.27.

All of the subjects were able to use the move-and-wait strategy and did so consistently. Occasionally, during the early practice sessions they tried moving slowly and attempted to use the delayed feedback, but, as this practice appeared to increase the time and cause more errors, it was abandoned.

As with the simple task, there was no sign of "unstable" behavior and no indication that the subjects were under more emotional strain than would be expected in any situation calling for skilled performance.

From Fig. 4.27, it can be seen that there was, on the average, a linear relation between completion time and delay. Moreover, the slope is very nearly $(m + 1)$ as would be predicted from the analysis; the grand average of $m$ being 7.51. The average $N$ was 7.71, and the closeness of $m$ and $N$ is reflected in the similar slope of the predicted and measured times. Results from the simple and complex tasks agree in being linear with delay.

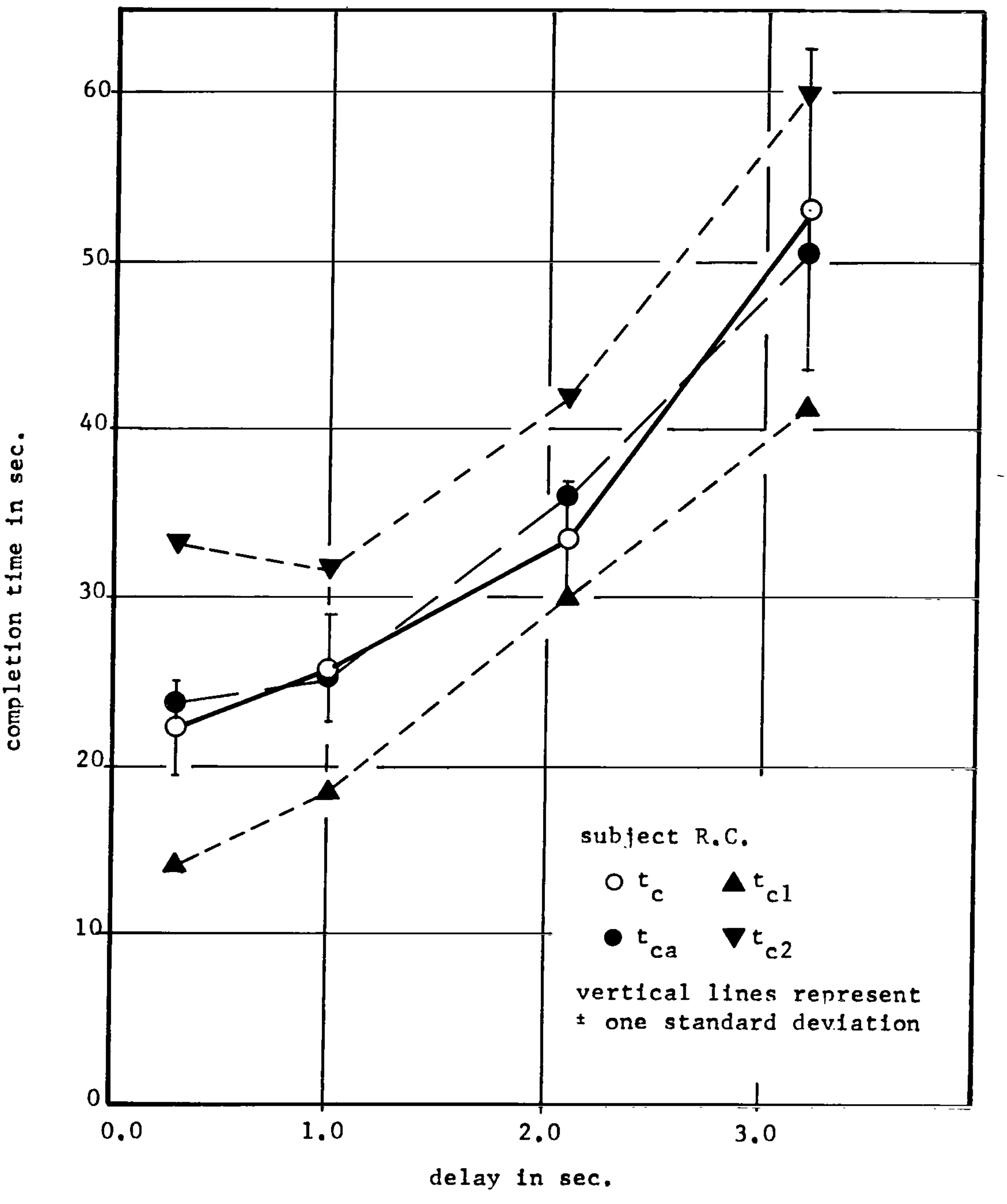



Fig. 4.23. Measured and Predicted Times, Experiment III, Subject R.C.

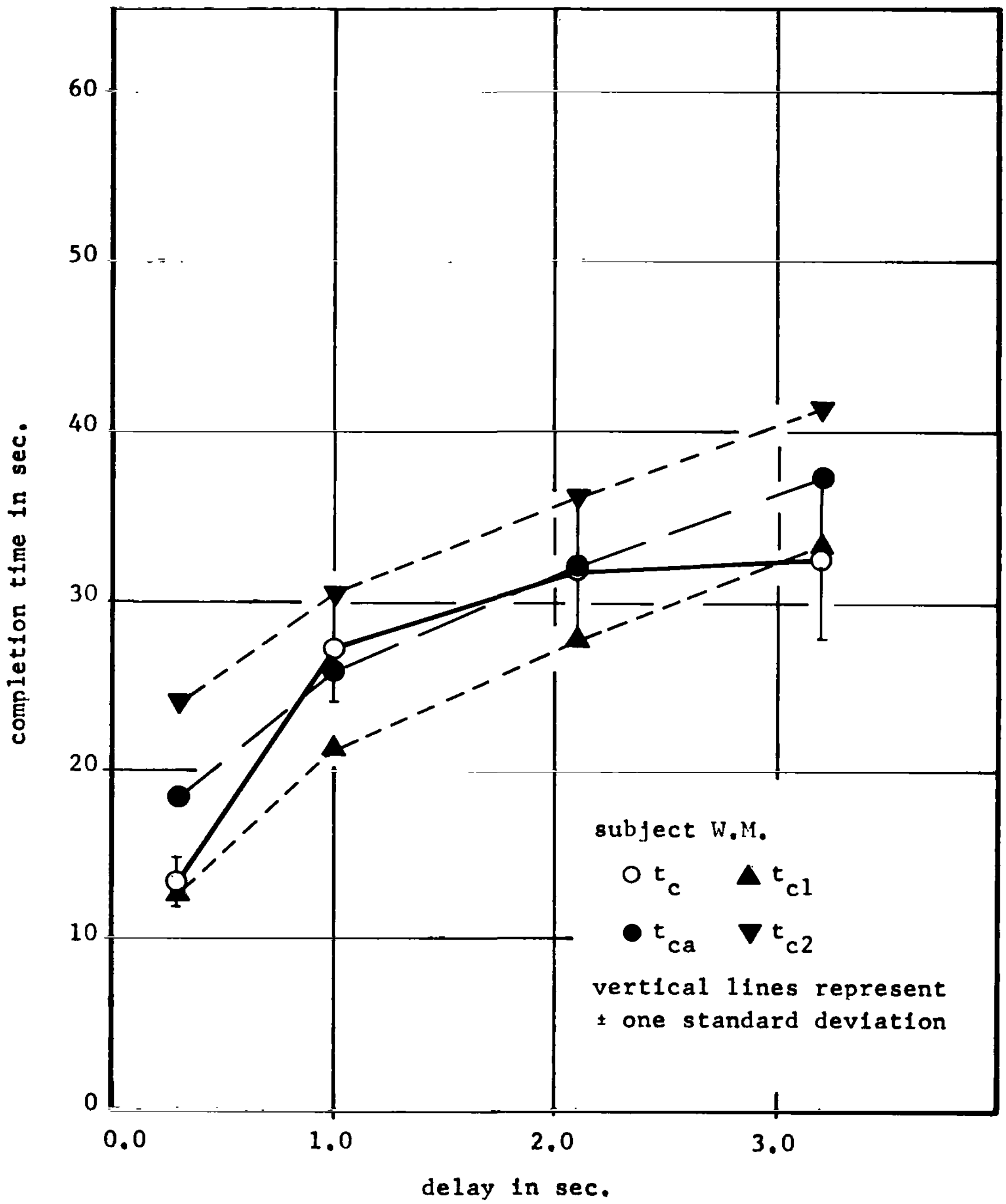



Fig. 4.24. Measured and Predicted Times, Experiment III, Subject W.M.

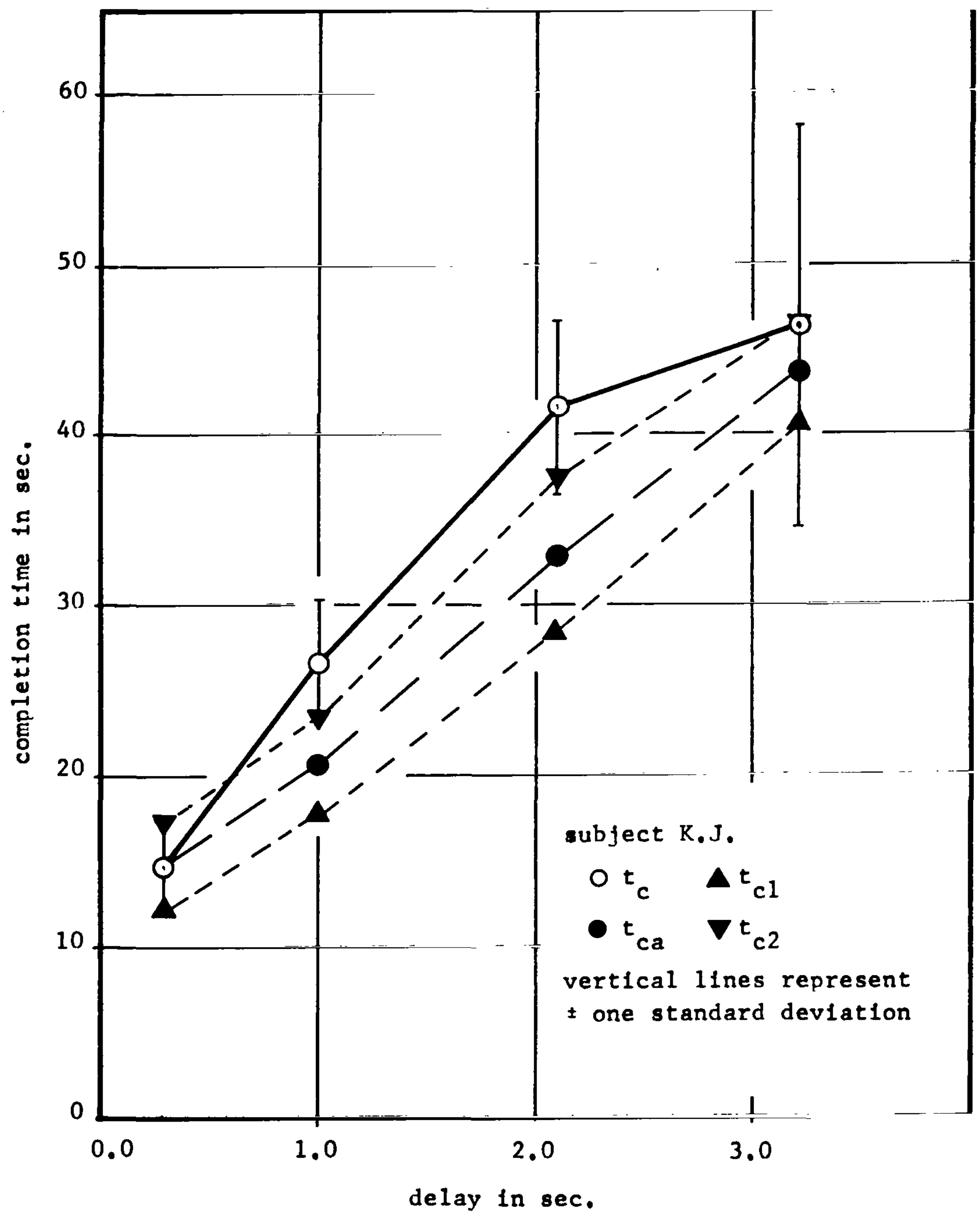



Fig. 4.25. Measured and Predicted Times, Experiment III, Subject K.J.

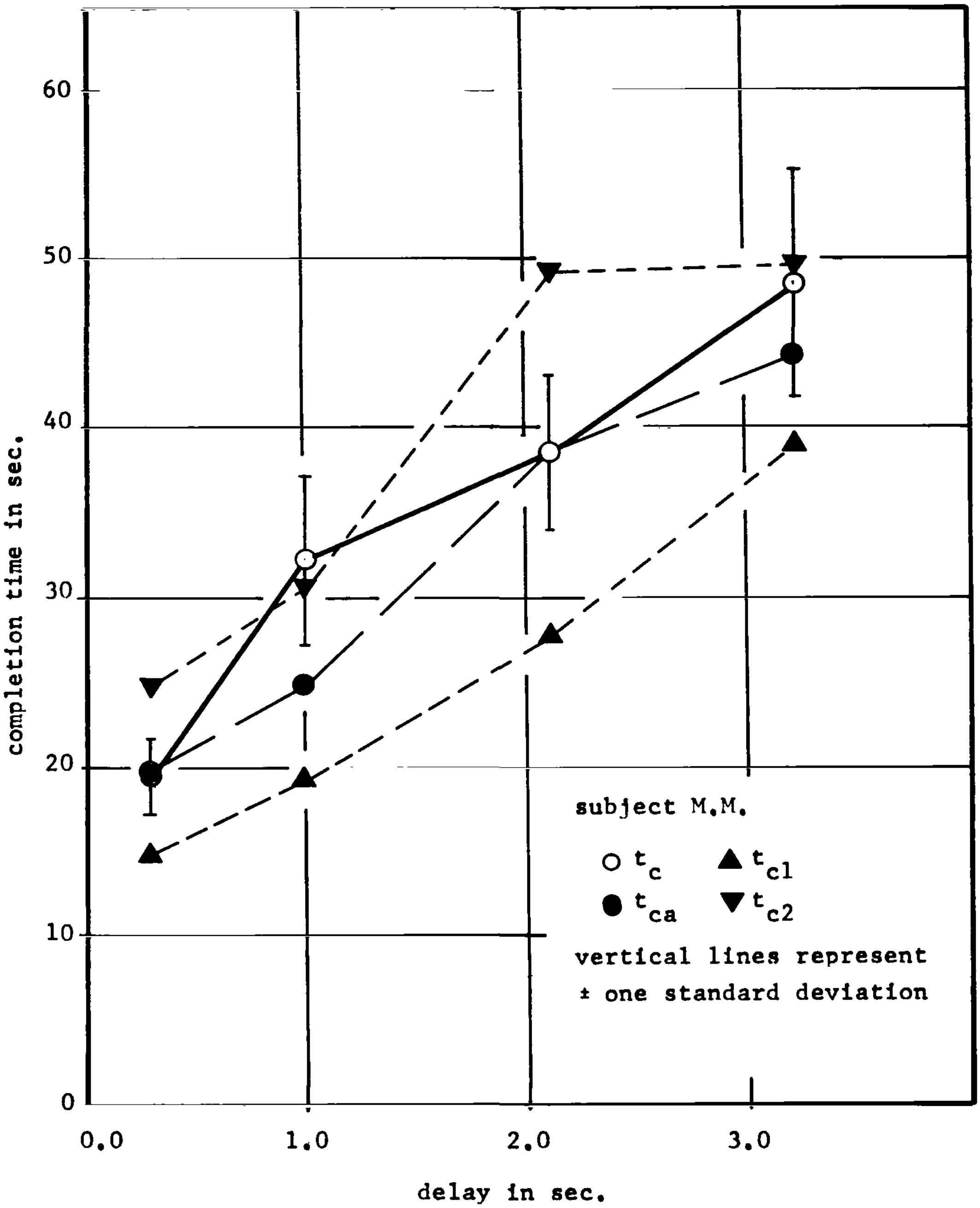



Fig. 4.26. Measured and Predicted Times, Experiment III, Subject M.M.

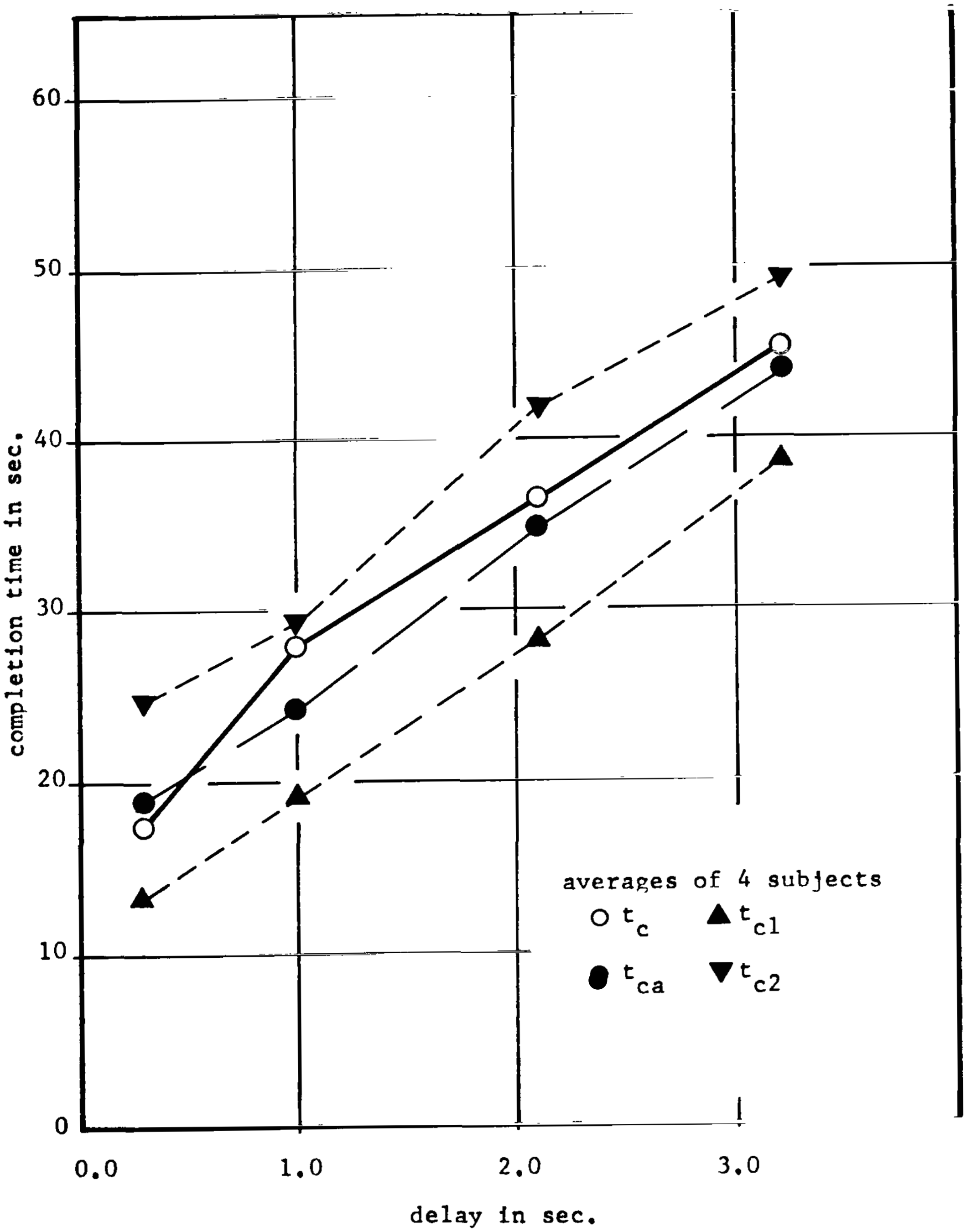



Fig. 4.27. Measured and Predicted Completion Times, Experiment III, Averages of Four Subjects

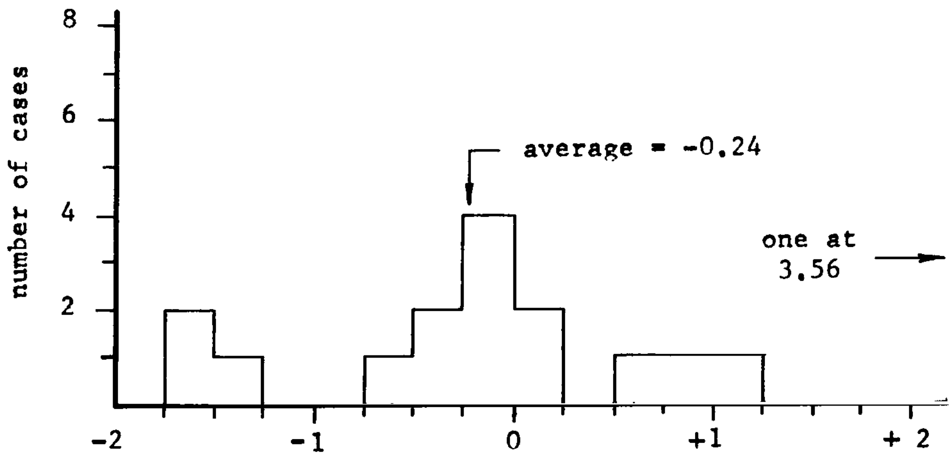
The measures N, $t_o$, $t_N$, and $t_r$ taken on each session were used in Eqs. (4.4) and (4.5) of Section 4.44 to predict the completion time with delay for that session. The results from each equation and the average prediction $t_{ca}$ are also shown in Figs. 4.23 through 4.26 for each subject. The averages over subjects are shown in Fig. 4.27. Again, the predictions $t_{c1}$ using $t_o$ are somewhat low and the predictions $t_{c2}$ using $t_N$ are somewhat high. The use of the time $t_N$ in the open-loop condition is fully justified in the present case since the relative importance of time and the number of times feedback was got, as set by the pay scale, was the same for delay and open-loop conditions.

Table 4.3 gives the means and standard deviations of the differences between the predicted times and the actual mean completion times, divided by the standard deviation of the ten delay trials. In addition, Fig. 4.28 shows the distribution of $(t_{ca} - t_c)/\sigma_{data}$. The one anomalous case, W.M. at 0.3 sec., was omitted from the calculations, and thus each entry in Table 4.3 represents 15 error terms. The prediction $t_{ca}$ is seen to be quite good; for the term $(t_{ca} - t_c)/\sigma_{data}$ has a mean of only -0.24 which a student's t test indicates is not significantly different from 0.0 at the 5 per cent level. The standard deviation of this term is only 0.79, with a 90 per cent upper confidence limit of 1.06. Hence, a prediction $t_{ca}$ based on ten measurements of the quantities $t_o$, N, and $t_N$, requiring 20 trials, is at least as good as one, and more likely almost as good as two actual trials with delay for predicting $t_c$, the mean of ten delay trials. This is in rather good agreement with the results of Experiment II. In fact, an F ratio test indicates that the difference between the variances of $(t_{ca} - t_c)/\sigma_{data}$ in the two cases is not significant at the 5 per cent level.

In Experiment II, 27 per cent of all the individual times fell between the two predictions $t_{c1}$ and $t_{c2}$. In the present experiment, these predictions were farther apart and 63 per cent of the individual trials fell between them. This difference can be accounted for by the fact that more open-loop moves m were required in the latter case. It would be expected that the difference between the average times $t_o$ and $t_N$ would increase roughly linearly with m since the discrepancy between them is presumably due to stopping and starting and moving more slowly (m + 1) times on the open-loop condition. However, the standard deviation of the times with delay could be expected to be approximately proportional to $\sqrt{m}$ since they represent the sum of times for (m + 1) moves on

| prediction error | mean | standard deviation |
|---|---|---|
| $\frac{t_{c1} - t_c}{\sigma_{data}}$ | -1.67 | 0.91 |
| $\frac{t_{c2} - t_c}{\sigma_{data}}$ | +1.19 | 1.44 |
| $\frac{t_{ca} - t_c}{\sigma_{data}}$ | -0.24 | 0.79 |

Table 4.3. Errors of Prediction in Units of the Standard Deviation of the Data, Experiment III




$\frac{t_{ca} - t_c}{\sigma_{data}}$ in increments of 0.25

Fig. 4.28. Histogram of Prediction Error Frequencies, Experiment III

the average. Hence the difference between $t_{c1}$ and $t_{c2}$ would increase with m more rapidly than the standard deviation of the data.

Figure 4.29 gives the average value of m as a function of delay, and also the average value of N obtained on the same sessions. N doesn't depend on delay, as would be expected, however m seems to show a peak at the 1.0 sec. delay. The counter-balanced design of the experiment with only one subject being given each order of presentation precludes a sensitive test of the effect of delay on m. There are, however, at least two reasons for supposing that the differences in the average value of m are not intrinsic.

1. The effect is not monotonic with delay, the most probable trend since the strategy was the same at each delay.

2. One subject showed almost the opposite effect.

Although it cannot be stated with certainty, the differences among the m values and also the inconsistencies in the subjects' completion time trends are probably due to a combination of random within-subject variation and to different treatment of subjects on different sessions. For example, the two highest values of m at the 1.0 sec. delay and the highest at both the 0.3 and 2.1 sec. delays were all results from sessions preceded by either one day or a weekend without the subjects using the manipulator. This should have been foreseen as a possible source of difficulty. Another possible source of unequal treatment of sessions and subjects could have been the experimenter's policy of pointing out the cause when a subject made an error and, if he persisted in making the same mistake, telling him how to avoid it. This was done because the cause of errors was not always readily apparent to the operator in the delay and open-loop conditions. It may, however, have contributed to the variability of the results.

In general, N was a rather stable measure and did not sensitively reflect the influences causing variations in m, although the two are, on the average, very nearly the same.

The per cent of trials that were in error, over all conditions, was 19.6. 59 per cent of the errors occurred with delay, 35 per cent with the open-loop condition and only 6 per cent with no delay. However, when the errors on open-loop and delay were paired by sessions, a paired comparison t test indicated that the difference between conditions was short of significance at the 5 per cent level. The subject with the most errors, W.M. made four times as many

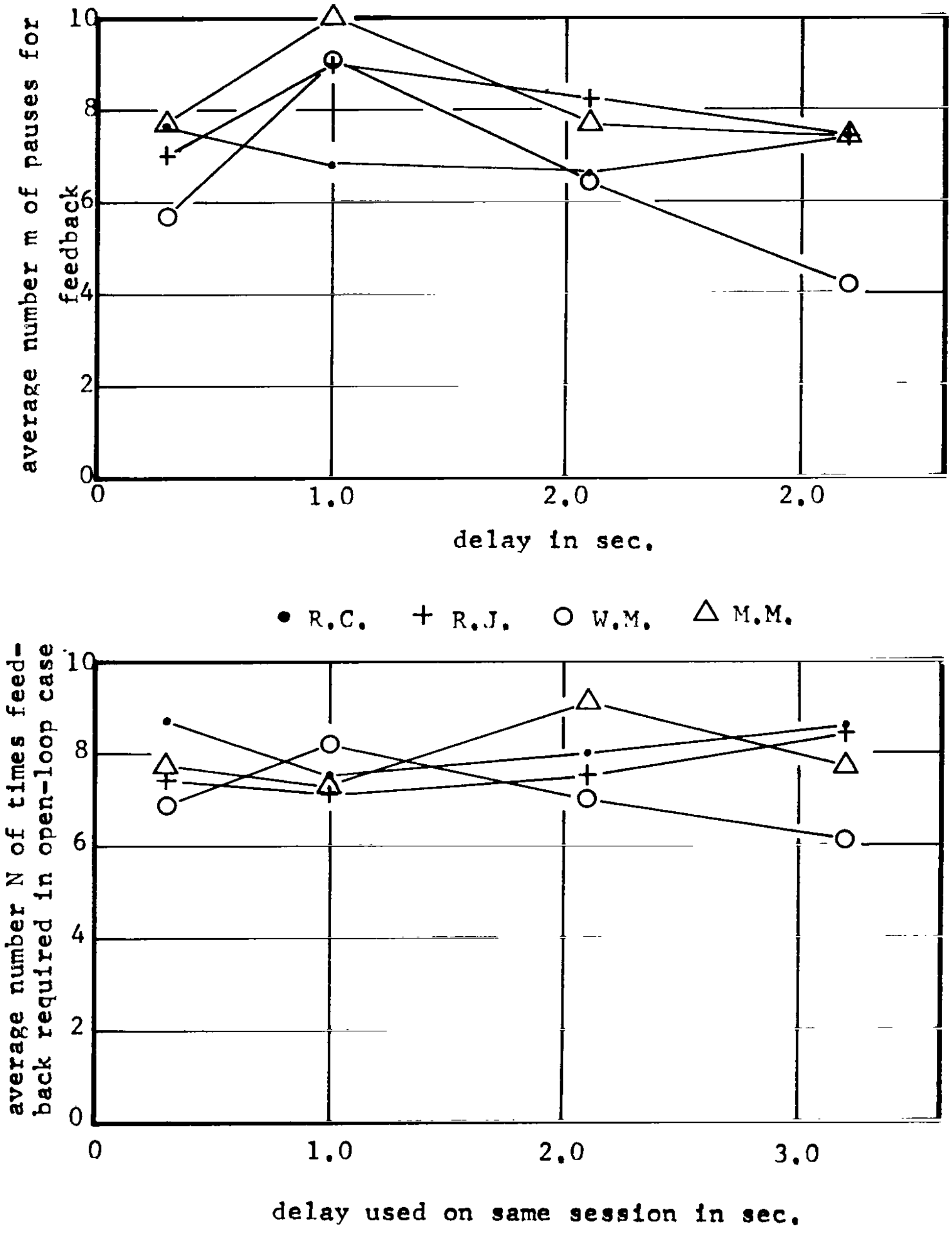



Fig. 4.29. Number of Times Feedback Obtained as a Function of Delay, Experiment III

as the one with the fewest, R.C. Fewer errors occurred at the 0.3 sec. delay than at any other - the most taking place with 1.0 sec. However, in view of the wide variability within and between subjects no firm conclusion about the effect of delay on errors is warranted. There was a tendency for subjects who made more errors with delay also to make more in the open-loop case, although only for one subject was there a high correlation between the number of errors on the open-loop condition and on the delayed condition for each session.

Two of the subjects, W.M. and R.C. showed an interesting tendency on later sessions to make some use of delayed feedback. Occasionally, they would make an open-loop move consisting of two actions, such as withdrawing tool 2 and turning it, and then pause as if to wait a delay time, but would wait only until the first action was successfully accomplished. At that point, apparently confident that the second action would be successful, too, they proceeded to make another move open-loop and then wait a full delay time for feedback. When m was counted, such pauses of less than a delay time were not included in the count. This use of delayed feedback had several characteristics:

1. It occurred only after considerable practice.
2. It was the exception rather than the rule, being tried only when the task was going well.
3. It seemed that there was no attempt to predict positions or velocities from the delayed feedback, only success or failure.

Since this behavior was not generally observed on earlier sessions, it is supposed that it may have been due largely to the fact that the same task was repeated many times.

## 4.6. Conclusions from Experiments with Delayed Remote Manipulation

### 4.61. Time-Accuracy Trade-Off

It has been conclusively demonstrated that, with a delay, accuracy sufficient to perform difficult and complicated tasks can be obtained at the expense of time when a strategy of moving open-loop and then waiting for correct feedback is used. This strategy was the most successful method found and was independently discovered and consistently used by eight of nine subjects. Four other subjects were initially instructed to use it and did so consistently. With the move-and-wait method, there was no indication of either "unstable" movements or emotional stress on the operators.

4.62. The Effect of Delay on Completion Time

The relation between completion time and delay was found to be essentially linear for a given task, the main effect being due to the time spent waiting for feedback. Both the number of these pauses and the time spent moving and making decisions appeared to be relatively insensitive to delay.

4.63. Predicting Completion Time for Delayed Remote Manipulation

It was found that the mean number of waits for feedback, m, could be fairly accurately estimated in the no-delay situation by N the average number of times an operator had to open his eyes for feedback when he was constrained to move only with his eyes closed, the open-loop condition. Two different estimates of the time required for moving could be got by using 1) $t_o$, the average completion time with no delay and 2) $t_N$, the average completion time in the open-loop condition. From an analysis of the move-and-wait strategy, two equations were derived for predicting completion time with delay from the above measures and the operator's reaction time, all of which can be taken in the no delay case.

As was foreseen, the prediction equation using $t_o$ was found to be an underestimate and the one using $t_N$ an overestimate of the average completion time with delay. However, the average of the two predictions each of whose parameters were based on 10 measurements was found to be as accurate an estimate of the mean of 10 trials with delay as approximately two actual trials would be. The accuracy of the prediction in terms of the variability of actual times with delay was essentially as good with a complex task as with a simple position and grasp task.

4.64. Manipulation Errors

On practically all the trials for which an error was scored, the task could have been completed. Had the only criterion for an error been inability to finish the task, the average times and the variability would have been greater. Since errors were generally more frequent for delay than for the open-loop case, the broader category of errors that was used probably tended to reduce the variability of the predictions somewhat over what it would have been had only cases in which the task could not be finished been discounted.

The extent to which the frequency of errors in the open-loop condition is an indication of the frequency of errors to be expected with delay is difficult to assess, especially since the greater number of errors in the delay case was statistically significant for the simple task but not for the complex. However, it would seem that there would be more opportunity for misjudgment with delay.

### 4.65. Predictor Displays for Manipulation with Delay

Manipulation time when there is a delay can probably be reduced substantially by providing the operator with a supplementary visual indication of the position in which he will observe the remote hand on the main display a delay time hence. The operator's view of the master hand would serve the purpose to some extent. If the main display of the remote site were by television, a "predictor" could be a superimposed view of a second manipulator, located near enough so that its response was not delayed, and seen from the same viewpoint.

A predictor display would not alter the fundamental characteristics of the manipulatory situation, nor would it remove the need for a move-and-wait strategy. It would reduce the number of times feedback would be required for movements whose tolerances are not determined by the size of objects being transported in the remote environment, e.g. movements with the remote hand empty. However, the predictor will always be inaccurate to some degree so that for motions beyond some tolerance level it will cease to be of use.

It is anticipated that even when a predictor display is used, an appropriate open-loop condition can be devised which will enable predictions of the completion time with delay to be made from measures of performance taken when there is no delay.

### 4.66. Limitations on the Conclusions

As with all experimental studies, the results that have been obtained apply strictly only to tasks and situations representative of those used in the experiments. However, there appears to be no *a priori* reason why the general conclusions should not apply to manipulators with more degrees of freedom than the one used or to tasks of a more practical sort than the ones investigated. The move-and-wait strategy would be the same and the predictions, based as they are on measures involving the operator-manipulator-task combination, should also be fairly accurate if the operator is familiar with the task and the equipment.

The smallest delay investigated was 0.3 seconds. For delays less than this, it may be the case that operators need not use a move-and-wait strategy to get good results, but may be able to predict ahead adequately and operate best in continuous fashion.

The writer believes that, with methods described in this report, practical remote manipulation can be accomplished in spite of a delay of 0.3 seconds or more and a good estimate of the time required can be obtained from measures taken when there is no delay.

The remote manipulator used in the present study was one which reproduced the operator's hand position. There is some evidence to suggest that even when the operator controls the remote device by turning motors on and off, the same move-and-wait strategy will be used with a delay, and a similar linear relation between completion time and delay will hold. This was found to be the case by four undergraduates in a term project supervised by the writer.[26] They used the task of passing the pen of an x-y plotter through single gates of different width by pressing switches which determined the direction of the pen's constant velocity motion. However, an adequate determination of the effects of delay on human-operator performance with on-off and rate controlled manipulators remains to be done.

# 5. FURTHER INVESTIGATIONS OF OPEN-LOOP PERFORMANCE

If the move-and-wait strategy is used for remote manipulation when there is a delay, a wait of one delay time is necessary whenever correct visual feedback is required, and the number of times such feedback must be obtained has been shown to be a strong determinant of the completion time, especially with long delays. The open-loop capability of the operator-manipulator combination, and the feedback requirements for various tasks are, thus, of considerable importance.

## 5.1. The Influence of the Manipulator on Open-Loop Performance

The number of times feedback from a task is needed when it can be got only between operations and not during them has been defined as N. It is a measure of the open-loop capability of the operator using a given system to perform a given task. The definition applies not only to remote manipulation but also to other self-paced control situations involving a human operator.

During the period when the primary feedback channel from the task is closed the operator must estimate his own control actions and also their effect on the system output. Any feature of the system which tends to degrade either of these estimates would tend also to increase N. In like manner, when feedback is being obtained, any feature of the system which degrades the feedback or makes assessment of the situation less accurate will also tend to increase N. Thus, it would be expected that open-loop performance would be determined by the system display and control properties as well as by the operator's own limitations.

### 5.11. Comparison of the Number of Times Feedback is Required with and without the Manipulator

In order to determine whether using the remote manipulator would increase the number of times feedback was required, a simple manual task was also performed by the two subjects who participated in the first delayed manipulation experiment.

The task was similar to the simple positioning one used with the manipulator and could also be assigned an index of difficulty I, where I = (2 x distance moved)/tolerance. It consisted of moving the point of a pencil from a starting position to within a tolerance region between two parallel lines perpendicular to the direction of movement and to the right of the starting point. The distance to the center of the tolerance region was 8 inches, and tolerances were chosen to give I values of 4, 5, 6, 7, and 8. Following a few practice trials, the number of open-loop moves, each made with eyes closed, needed to get within tolerance was recorded for 30 trials at each value of I. I was taken in increasing order. The average number of moves M for both subjects J.K. and E.C. as a function of I is shown in Fig. 5.1 with the values of N from the manipulator task for comparison. M is seen to be consistently larger than N by a factor of about 1.4 for J.K. and about 1.2 for E.C.

The comparison between M and N is not altogether correct in this case. In the task used with the manipulator, the final open-loop grasp movement sometimes included a correction to put the fingers within tolerance. Hence the number of moves M to get within tolerance on the manual task corresponds to a value between N and N + 1 for the block grasping task. Had there not been this difference between tasks, M would have been even lower in relation to N. Moreover, as is shown in a subsequent section, the number of moves to get within tolerance on the manual task is dependent upon the distance moved, with longer distances requiring fewer moves on the average at a given index of difficulty. No effect of distance was evident from the analysis of variance performed on the data from the original delayed manipulation experiment probably because it was concealed by the variability associated with using the manipulator with the delay.

There are at least three factors which, although they were not separately evaluated in the experiment, probably were responsible for feedback being required more often in the manipulator case:

1. Physical characteristics, both static and dynamic, of the manipulator master control.
2. The greater viewing distance and consequent smaller visual angles when the manipulator was used. Poorer depth perception due to distance might be a factor in more complex tasks, and has been shown to affect manipulation time when there is no delay.[27]
3. The fact that the tolerance region was explicitly displayed

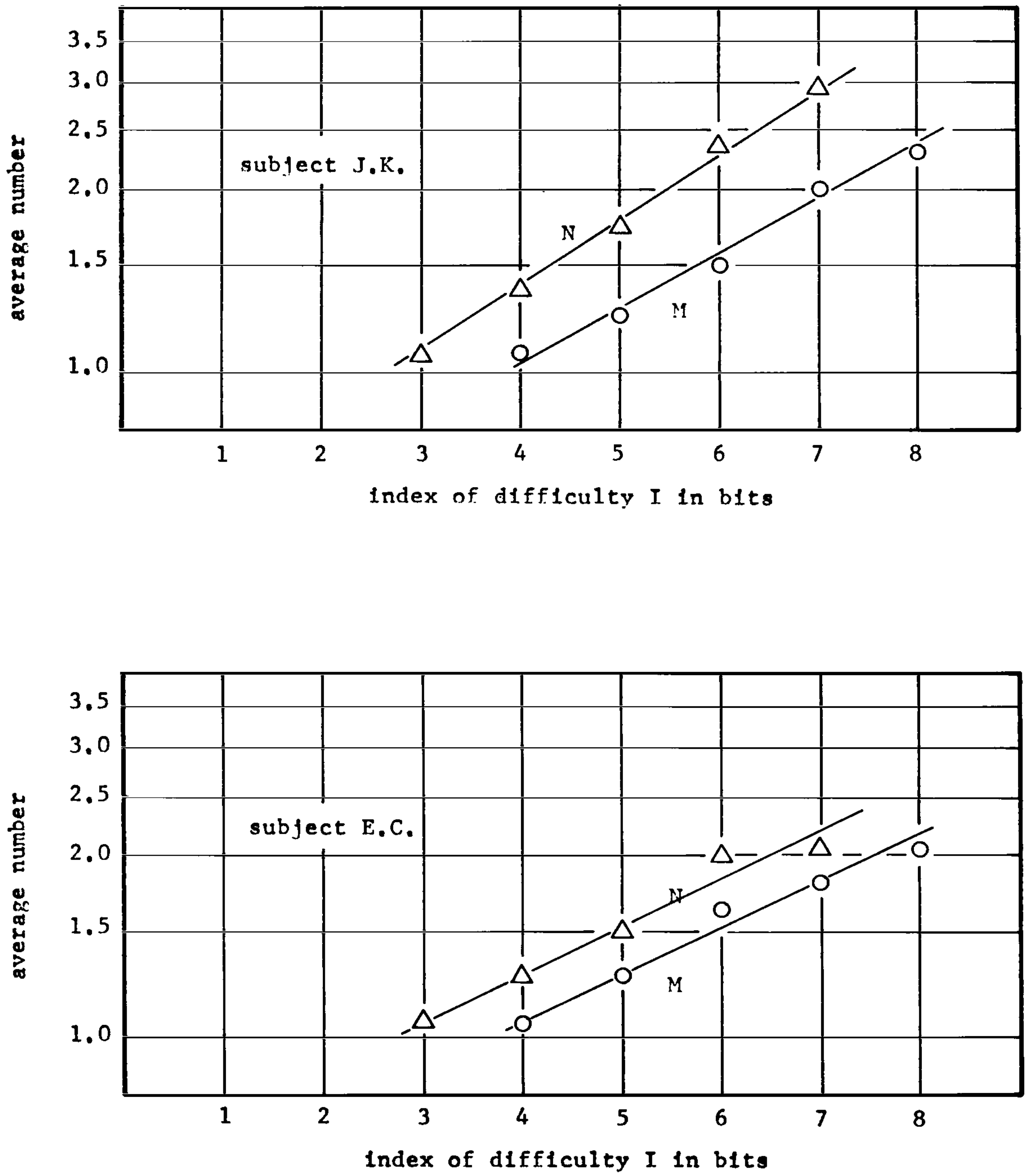



Fig. 5.1. Comparison of Feedback Requirements with and without the Manipulator, Experiment I

in the manual task, but was the difference between block width and finger opening for the manipulator task.

The influence of the control's characteristics is of special significance; for in the design of remote manipulators to be used with a delay it would be important to avoid those features which might reduce the operator's ability to perform without visual feedback.

### 5.12. The Effect of Manipulator Control Characteristics on the Number of Open-Loop Moves

Objectives:

A number of experiments concerned with the effects of manipulator control properties on open-loop performance were done by a group of four undergraduates, L. Logterman, R. Roberts, D. Walton, and J. Weil, in connection with a course in experimental engineering.[28] The writer was their project advisor. The experiments were intended to assess the effect of several common control characteristics on the number of open-loop moves needed to achieve a given tolerance from a given starting distance. The preliminary hypothesis was that linear dynamics such as inertia would have no appreciable affect on performance, but that nonlinearities such as static friction or backlash would substantially increase the number of moves required.

Experiment:

The investigators used a model manipulator master hand with one-degree-of-freedom consisting of a light aluminum carriage mounted on model railroad trucks which ran on a straight strip of H.O. gauge track. Extending from one side of the carriage was a pointer, and the task required of a subject was to position the carriage by hand so as to move the pointer to the left from a fixed starting position to within a tolerance specified by two parallel lines perpendicular to the direction of motion. The subjects were required to close their eyes while moving the device, and were permitted visual feedback only between moves. The number of moves was recorded on each trial.

There were six conditions:

1. Inertia - a 4.5 lb. weight was placed on the carriage.
2. Friction - the carriage was clamped to a wire stretched lengthwise over the track, requiring a 1.75 lb. starting force to move the carriage.

3. Backlash - the pointer dragged lightly on the paper and on each reversal of direction, the pointer responded only after the carriage had moved 0.5 inches.

4. Constant Force - a long model airplane rubber was attached to the end of the carriage providing an approximately constant force of 2 lb. to the right.

5. Combined - inertia, friction, and backlash were all applied.

6. Standard - the carriage with its low mass and negligible friction was used alone.

When there was backlash, an approximately white noise was presented to the subject through earphones to mask any audible feedback from the apparatus. It should also be noted that the backlash, unlike the other properties, could not be detected kinesthetically.

With each condition, the set of the 11 distance-tolerance combinations was presented nearly 50 times. Each time the set was presented in the same order but the same distance was never taken twice in succession.

Two of the investigators acted as subjects. Each had some prior practice. The conditions taken by each are listed in order below.

| | R.R. | J.W. |
|---|---|---|
| 1. | standard | standard |
| 2. | inertia | constant force |
| 3. | backlash | backlash |
| 4. | friction | friction |
| 5. | combined | combined |
| 6. | standard | standard |

Results:

Figures 5.2 through 5.4 give the results for each distance and tolerance graphically. The average number of moves $M$ is plotted on a logarithmic scale <u>vs</u>. the index of difficulty I for each movement distance. The most obvious result is that there is a consistent effect of distance, with the longer distances

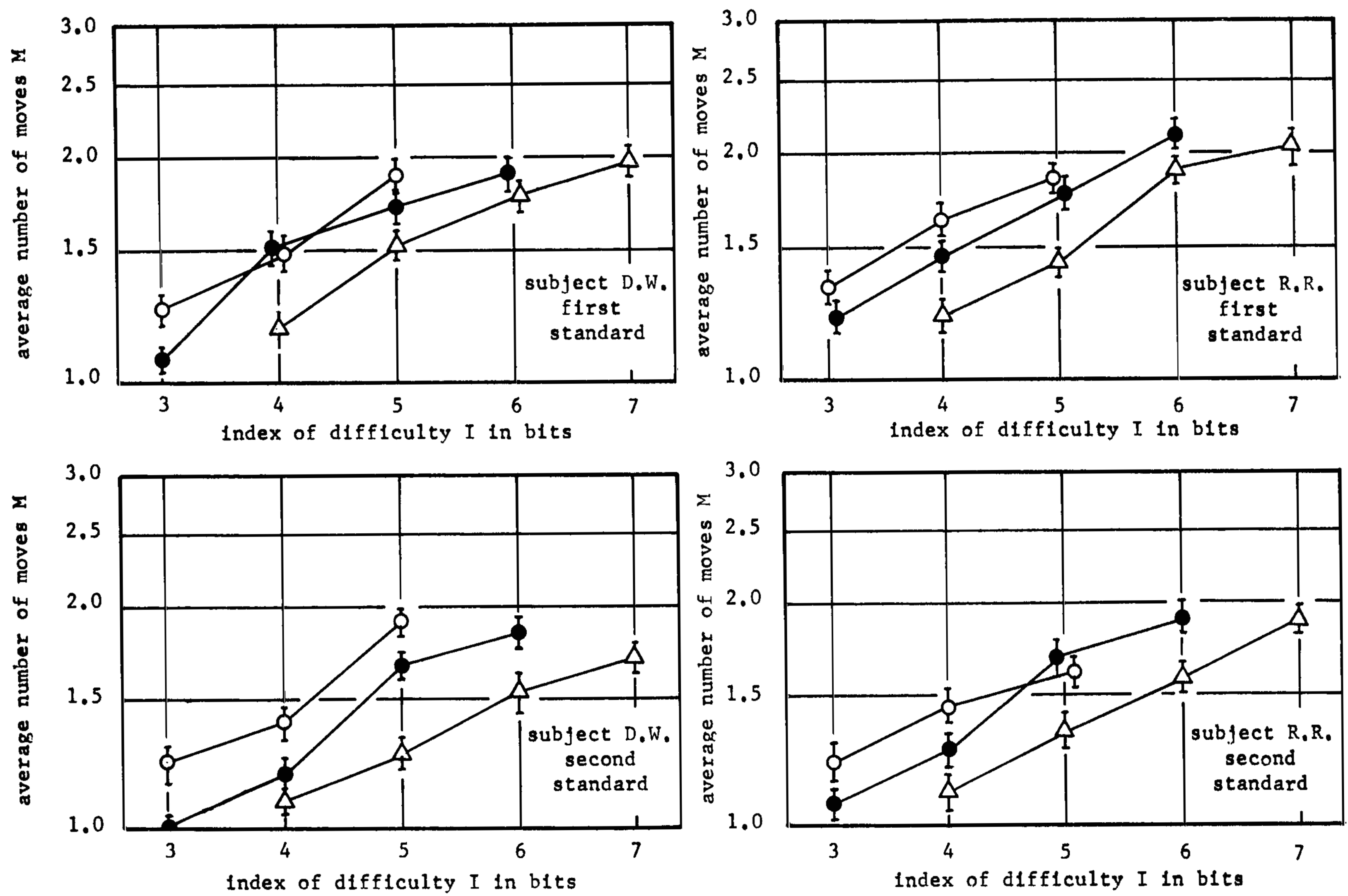



Fig. 5.2. Number of Open-Loop Moves, Control Properties Experiment, Standard Condition
(starting distance: O 4 in., ● 8 in., Δ 16 in. vertical lines = ± one std. dev. of the mean)

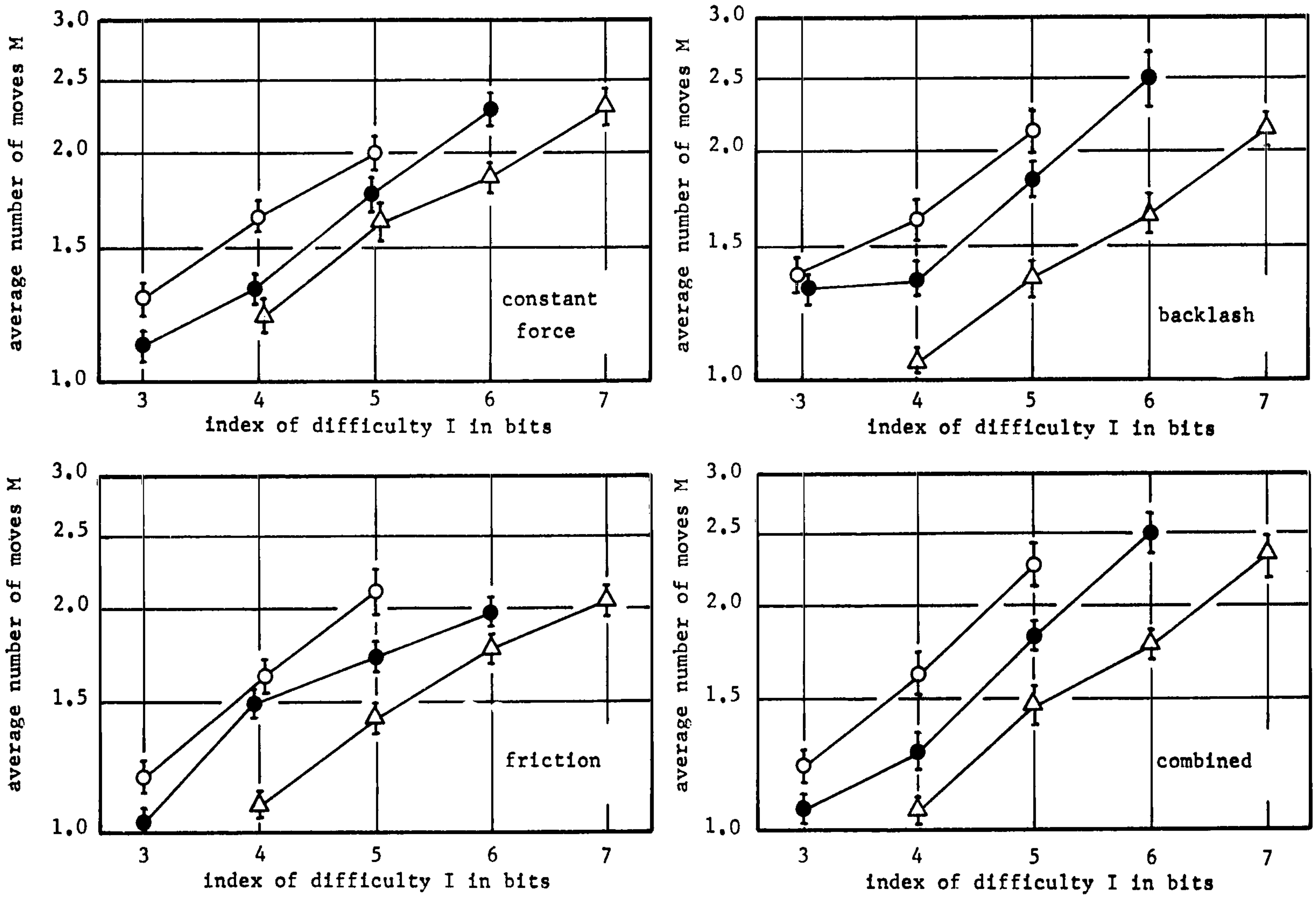



Fig. 5.3. Number of Open-Loop Moves, Control Properties Experiment, Subject D.W.
(starting distance: 0 4 in., ● 8 in., Δ 16 in. vertical lines = ± one std. dev. of the mean)

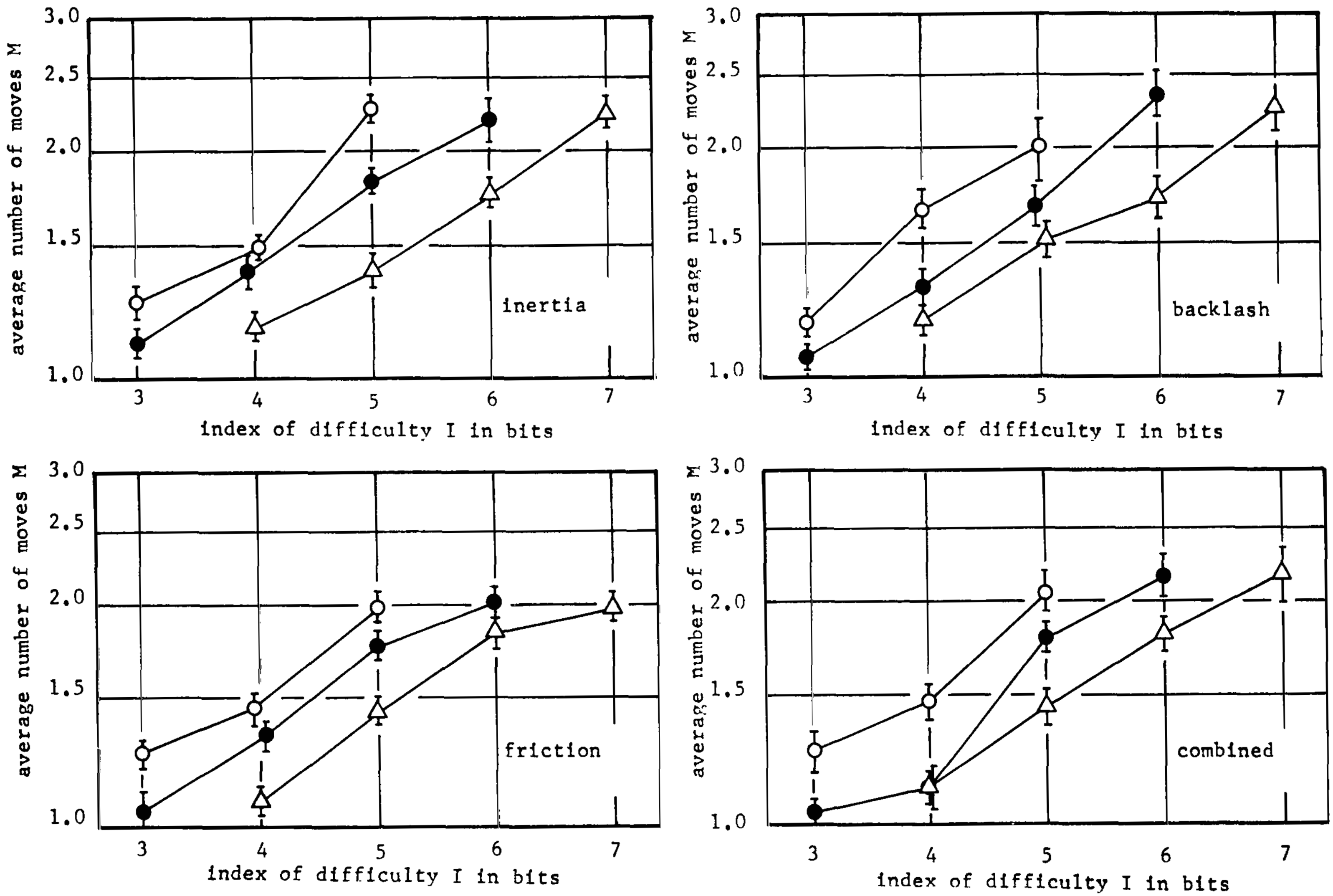



Fig. 5.4. Number of Open-Loop Moves, Control Properties Experiment, Subject R.R.

(starting distance: O 4 in., ● 8 in., Δ 16 in. vertical lines = ± one std. dev. of the mean) requiring fewer moves at the same level of I. For each distance, the log of M is roughly linear with I.

The data was tabulated to give the frequencies with which 1, 2, and 3 or more moves were required at each distance and tolerance under the different conditions. The frequencies were summed over distance and tolerance and the resulting distribution from each test condition was compared with the distribution from the combination of the two standard conditions for each subject. A chi-square test showed that the differences between the distributions of M from the standard and from the experimental conditions were significant beyond 1 per cent, with the exception of the friction condition with subject R.R. which tested short of significance at the 10 per cent level. Friction also had the smallest effect for J.W. The characteristic giving the largest effect in terms of chi-square for both subjects was backlash.

The averages of M over all distances and tolerances at each condition are given in Table 5.1

| Condition | R.R. | J.W. |
|---|---|---|
| standard 1 | 1.619 | 1.580 |
| inertia (R.R.) } constant force (J.W.) | 1.658 | 1.675 |
| backlash | 1.634 | 1.681 |
| friction | 1.565 | 1.615 |
| combined | 1.602 | 1.695 |
| standard 2 | 1.482 | 1.442 |
| average standard | 1.551 | 1.511 |

Table 5.1. The Average Number of Open-Loop Moves for Different Control Properties

Although the effect of the control characteristics was found to have a significant effect on the distribution of the number of moves, the effect in terms of the average number is remarkably small. Adding a 4.5 lb. weight, 0.5 inch backlash and 1.75 lb. static friction increased the number of moves by less than 13 per cent over the average of the standard conditions for J.W. and less than 4 per cent for R.R. For both subjects friction had the least effect on the average M. Inertia had the greatest effect for R.R. and constant force for J.W., possibly because of their being first in the series. Thus both linear and non-linear characteristics have a detectable but relatively small effect on the average number of moves M and hence would not strongly affect performance with delay. The class of properties for which this is true and the extent of the effect with other controls have yet to be determined.

## 5.2. A Statistical Model for the Number of Open-Loop Moves to Achieve a Given Tolerance

In order to investigate further the open-loop capabilities of the human operator, a statistical model was made for performance on the one dimensional task of achieving a given accuracy about a target by a series of moves--visual feedback being permitted only between moves. The basic assumption of the model is that each move is an independent attempt by the subject to hit the center of the target region from whatever distance remains following his previous moves.

If successive moves are independent, then, if tne distribution of the end points of moves were specified as a function of target distance, the average number of moves required to get within a given tolerance from a given starting distance would be determined. The appropriate equations for the expected number of moves have been written for the case of normal distributions whose mean is the target center and whose variance may be a function of the distance and are given in Appendix A. The difficulty of solving these equations in closed form suggests the more direct approach of using a digital computer to draw, Monte Carlo fashion, from the appropriate distributions until the tolerance requirement is satisfied, count the number of "moves" it has made in this way, and, having done this many times, tabulate the average number of moves. For a large number of trials the average will be a good approximation to the expected value.

### 5.21. The Distribution of the End Points of Open-Loop Moves as a Function of Distance

The first step was to determine the distribution of move end points as a function of the distance to be moved. This was done by having two subjects, J.K. and W.F., the writer, make moves with their eyes closed from a starting point to targets 0.5, 1.0, 2.0, 4.0, and 8.0 inches distance. Approximately 100 moves were made at each distance. Distances were randomly interspersed to approximate better the actual case, since it was found that significantly greater accuracy could be got if one distance was repeated again and again. The region about the target was divided into incremental widths of one millimeter and all hits within each increment were combined.

It was hypothesized that the distributions would be normal, with possibly some constant error, and that the variance of the distributions would be proportional to the distance. The latter assumption is based on the notion that an open-loop move to a target a distance d units away would be logically equivalent to d independent moves of one unit, one after another. Hence, if the distribution for a unit move were normal with variance $\sigma_1^2$, then by virtue of the fact that the variance of the sum of independent normal variates is the sum of their variances, moves of distance d would have a variance $d\sigma_1^2$. This idea was originally proposed by Cattell[29] as a substitute for Weber's law.

Histograms representing the move end points were made for the two subjects. Because the histograms were so symmetrical and their means differed so slightly from the target center, i.e. the range effect[30] was very small, it was decided that the distributions could be accurately assumed normal about the target. The variance as a function of target distance is plotted in Fig. 5.5. It is seen that the relation

$$\sigma^2 = Kd$$

is a good description, where K is a constant, $\sigma^2$ is the variance, and d is the distance. The variances for a case in which the same target distance was repeated on each trial is also shown in the figure, and can be seen to be substantially smaller than when distances are randomly ordered.

### 5.22. The Computer Program

The second step was the preparation of a program to implement the model. The programmed sequence was essentially:

1. Take the starting distance.
2. Draw a random number from a unit normal distribution (representing a move).
3. Multiply the absolute value of the random number by the standard deviation for the starting distance to give

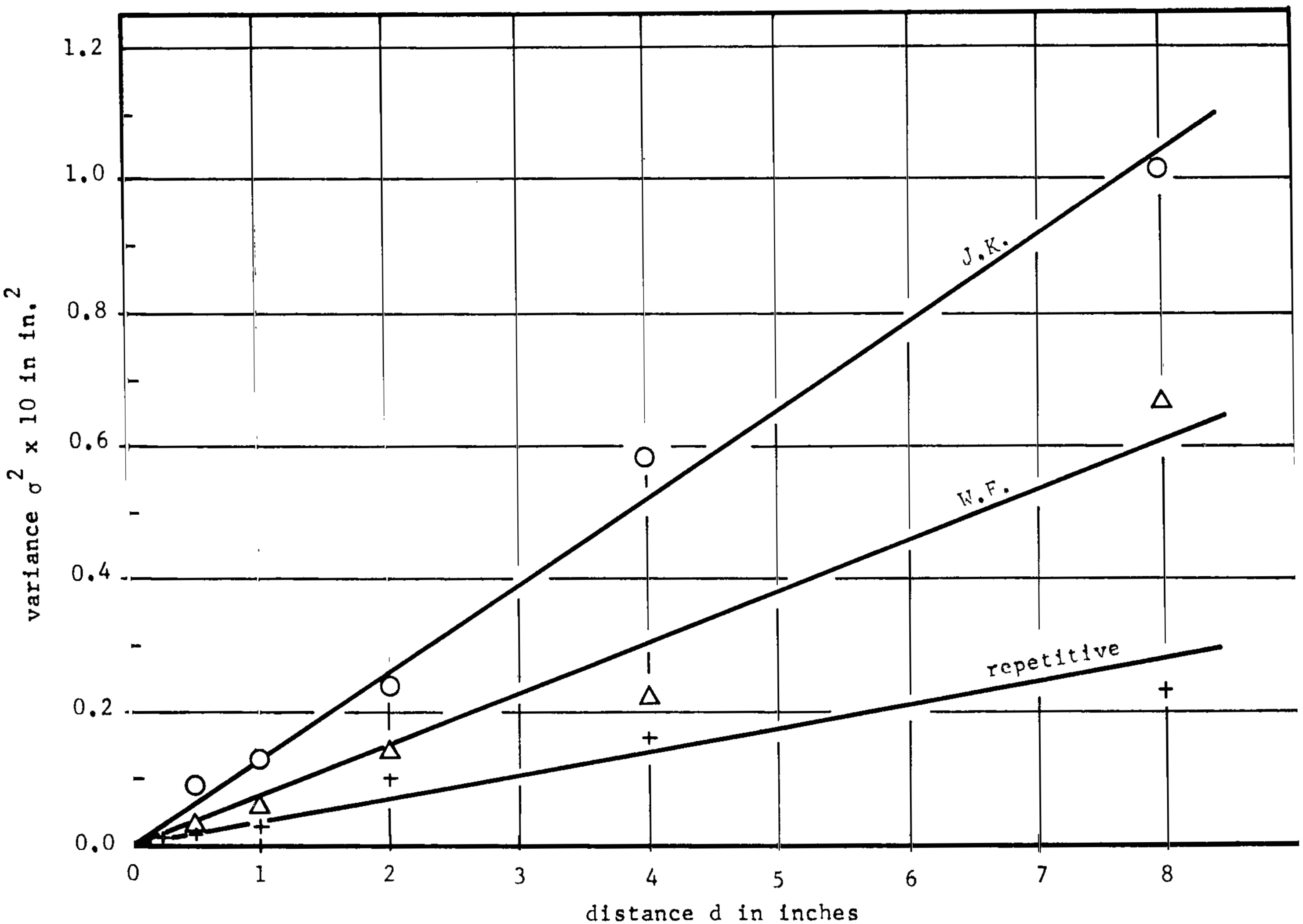



Fig. 5.5. Variance of Open-Loop Moves as a Function of Target Distance

the remaining distance to the target.

4. Check to see if this distance is less than the tolerance.

5. If it is less, the number of moves is 1, if it is not, the number of moves is at least 2, and steps 1 through 5 are repeated as often as necessary, but each time with the new distance in place of the starting distance.

### 5.23. Comparison of Results from the Model with Experimental Data

The program was first run using the standard deviation function $\sigma = K'(d)^{0.5}$. The constants K' were got from straight lines fitted to the variance data by least squares.

| Subject | Standard Deviation |
|---|---|
| J.K. | $\sigma = 0.114(d)^{0.5}$ inches |
| W.F. | $\sigma = 0.087(d)^{0.5}$ inches |

For each subject, the program predicted the average number of moves for 100 trials at each of five task information levels, 4, 5, 6, 7, and 8 bits for each of 3 starting distances, 4, 8, and 16 inches. As a check, the program was run a second time for each subject. The results were almost identical, and were averaged. Care was taken that an independent set of random numbers was generated for each run.

For comparison with the model, the same two subjects performed the previously described task of making open-loop moves with a pencil to get within a specified tolerance region. The same distances and tolerances were used as in the computer program with the exceptions that neither subject performed at the smallest tolerance, and J.K. did not perform with the 16-inch starting distance.

Figures 5.6 and 5.7 show the average number of moves M from the model and the experiment. Each experimental point represents the average of 25 trials for J.K. and 50 trials for W.F. The predictions from the model reflect quite accurately for both subjects the effect of starting distance and also the general relation between M and task difficulty I at each distance. The agreement between values leaves something to be desired, inasmuch as the model consistently underestimates for J.K., and overestimates for W.F.

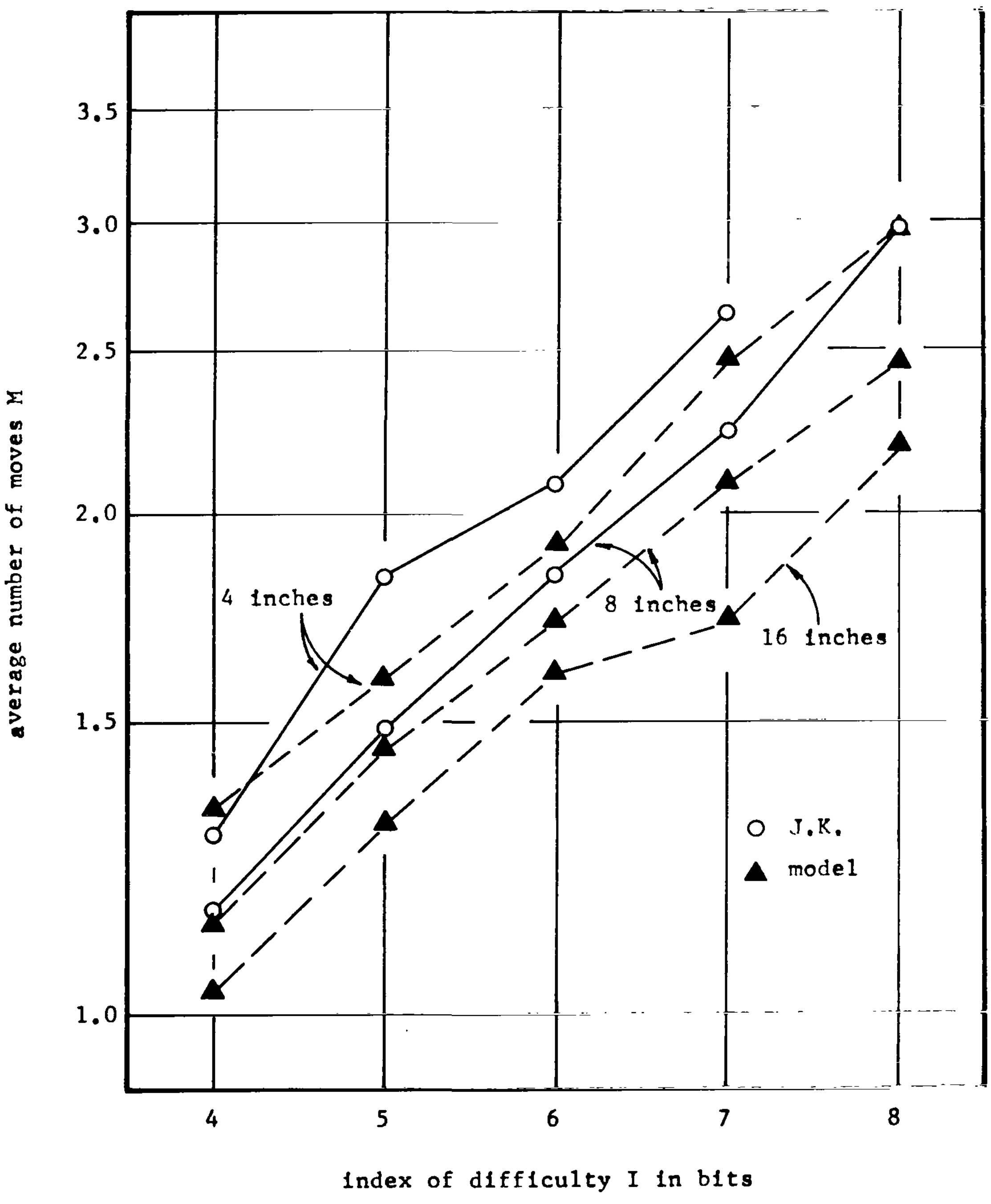



Fig. 5.6. Number of Open-Loop Moves M from Model and Subject J.K.

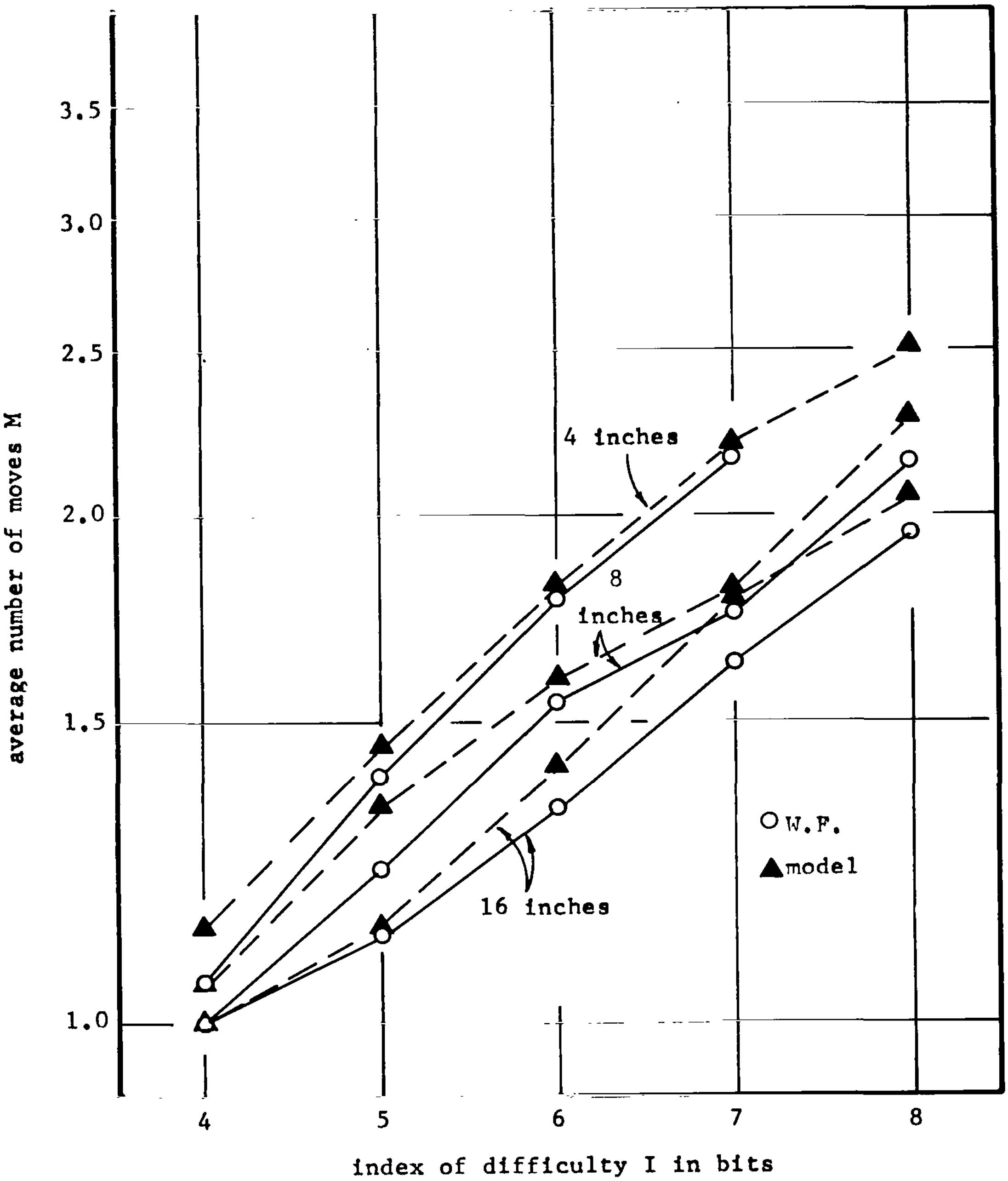



Fig. 5.7. Number of Open-Loop Moves M from
Model and Subject W.F.

Results from the same kind of manual open-loop move experiment with J.K. made a year before, Fig. 5.1, were compared with the more recent data, and a very large difference was found, larger than the discrepancy between the model and the recent data. It is thought that the parameter in the variance expression may not be constant from day to day, and that during the time interval (several days) between taking the variance data and the open-loop data, the value changed. Hence an attempt was made to get closer agreement between the model and the data by changing the value of the parameter. The adjusted standard deviations used in the program were:

| Subject | Standard Deviation |
|---|---|
| J.K. | $\sigma = 0.130(d)^{0.5}$ inches |
| W.F. | $\sigma = 0.075(d)^{0.5}$ inches |

Figures 5.8 and 5.9 show the average number of moves from the program (1000 trials at each distance and tolerance) with the data from the two subjects. It is apparent that the adjusted model fits the data quite well.

The distributions at each distance and tolerance of the number of times 1, 2, or 3 or more moves were required by subject J.K. were tested by chi square against the distributions given by the adjusted program. The tests showed that the differences between the experimental distributions and the computed ones were not significant at even the 10 per cent level.

As a check on the use of the relation $\sigma^2 = Kd$ for the model, the variance data for W.F. was plotted as $\sigma$ vs. d and the best fitting linear relation was got by least squares, giving $\sigma = (0.025 + 0.054d)$ inches. With this relation, the computed number of moves was found to be very much greater than the experimental for the smaller tolerances, especially at the 4 inch distance. This would indicate that the linear expression for $\sigma$ is far too high at the low distances, and hence less adequate than the relation $\sigma^2 = Kd$.

5.24. Conclusions

It is concluded that the process of making open-loop moves in one dimension to achieve a given tolerance can be modeled with considerable accuracy as one in which the end point of each move is an independent draw from a normal distribution about the target whose variance is proportional to the distance to be moved. Further, the constant of proportionality is a parameter

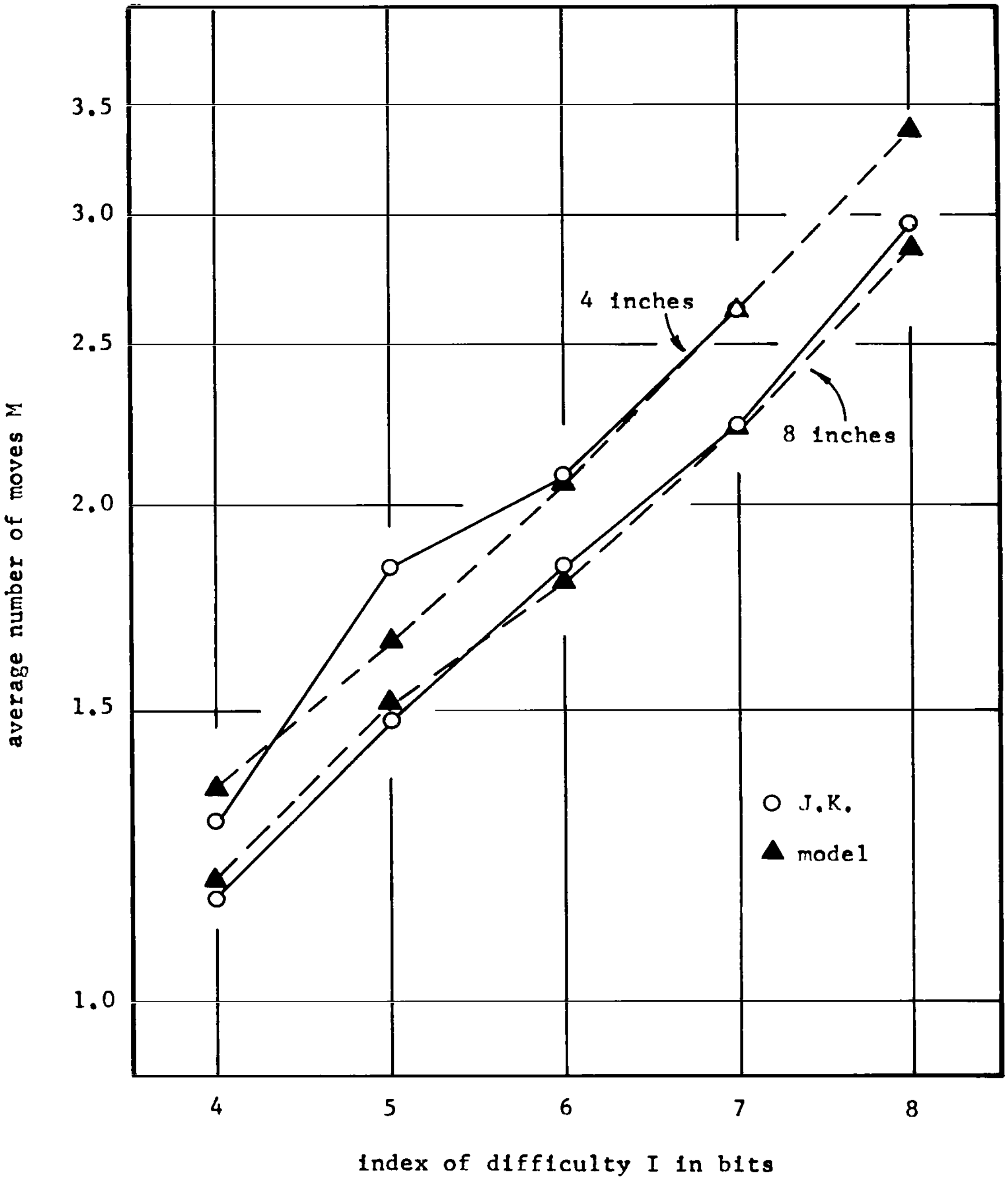



Fig. 5.8. Number of Open-Loop Moves M from Adjusted Model and Subject J.K.

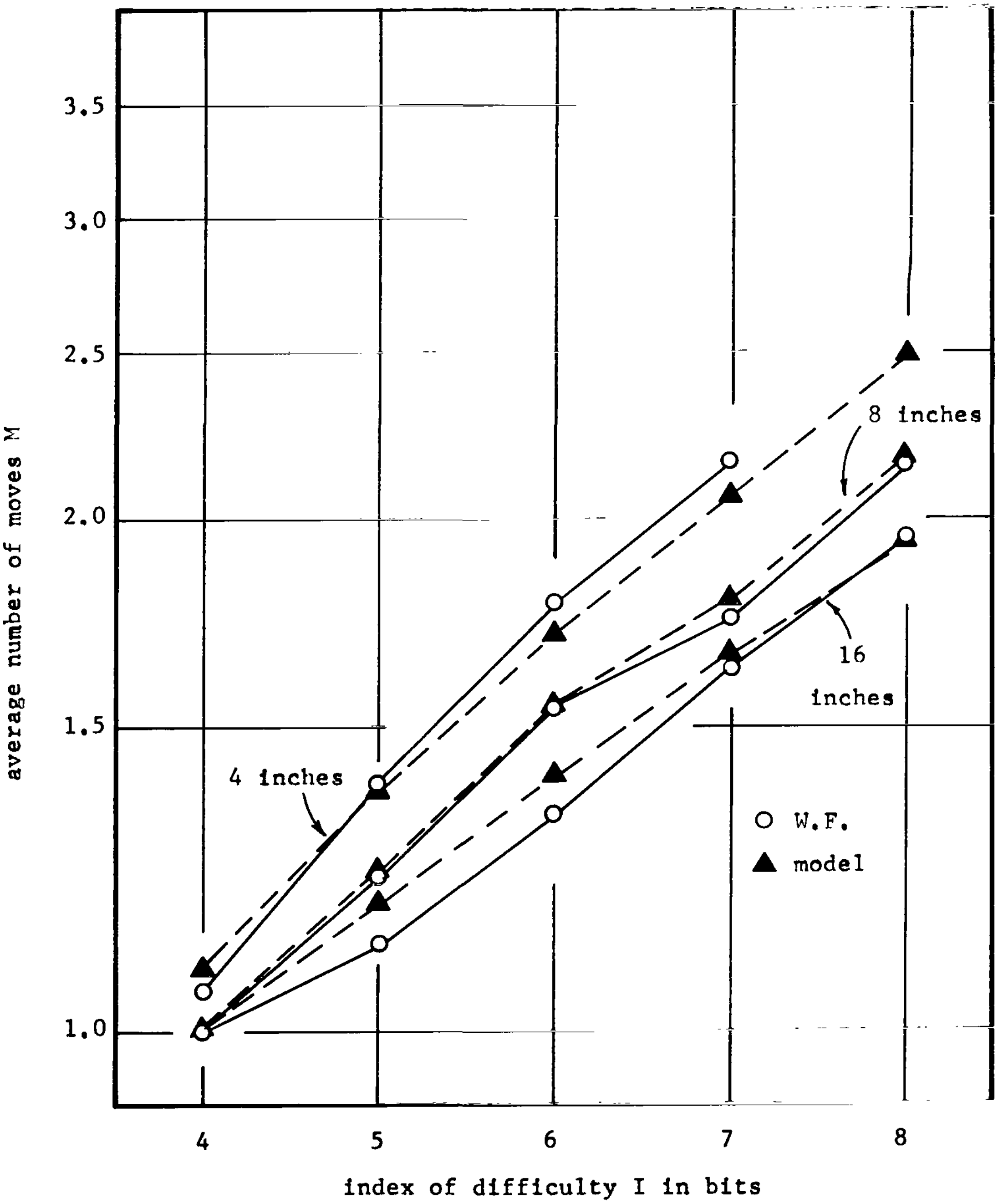



Fig. 5.9. Number of Open-Loop Moves M from Adjusted Model and Subject W.F.

whose value probably reflects both inter-subject and intersession differences.

## 5.3. Intermittent Feedback

In an attempt to find a simple way to measure N, the least number of times visual feedback is required for open-loop task performance, a number of tasks were performed under the sole illumination of a periodically flashing strobe light, whose flash intensity and duration were essentially independent of flash rate over the rates used. The intensity of illumination, depending on how the lamp was placed, varied with the task. The duration was nominally 0.8 microseconds between the 1/3 peak intensity points.

It had been hypothesized that as the flash rate was reduced, the total number of flashes required to perform a task would decrease, until, at a rate of about 1 to 2 per second, performance would become discrete, and the number of flashes required would level off at N.

Contrary to expectation, it appeared that the relation between flash rate, r, and the number of flashes required to perform a task, n, is best expressed by the relation

$$n = N + t_o r \tag{5.1}$$

where $t_o$ is the time required to perform the task under normal illumination. Further, the result appeared to be relatively independent of the kind of task used, providing that it was one requiring visual monitoring. The linear relation was especially surprising in light of the fact that there was no discontinuity associated with the change from discrete movements at low flash rates to continuous motion at the high rates.

### 5.31. Experiment

To examine the hypothesis that $n = N + t_o r$, two experiments were performed using entirely different tasks. The first task consisted of following a 1/4 inch wide sinuous path with a pencil. Trials in which the subject did not keep within the path were repeated. The path is shown in Fig. 5.10. The second task was to pick up, one at a time with long nosed pliers, five No. 6 hex nuts randomly placed within a 1 3/4 inch diameter circle and drop them through a 7/16 inch diameter hole 4 inches away. If the pliers touched the area around the hole or if a nut were dropped without going into the hole, the trial was repeated.

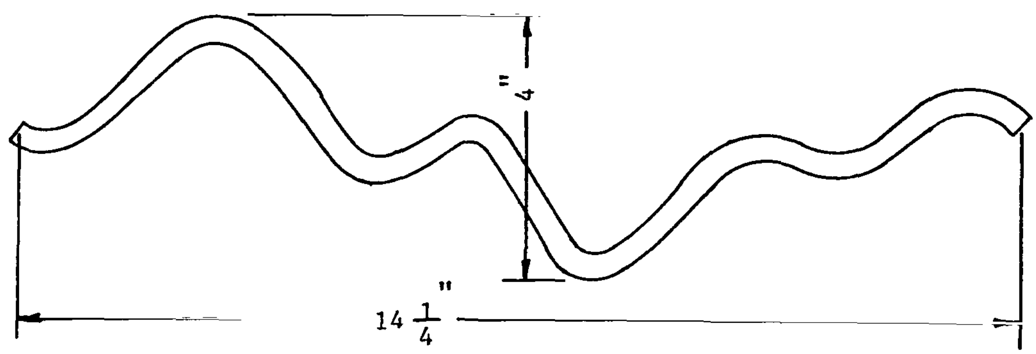



Fig. 5.10. Path Used in Stroboscopic Illumination Experiment

For the path-following task there were nine conditions. The task was illuminated by a strobe light at rates of 0.25, 0.5, 1, 2, 4, and 8 flashes/sec., and also with normal room lighting. Subjects were instructed to do the task as quickly as possible without error. In addition, two other conditions were:

1. (Self-paced) The task was performed by having the subject illuminate the workspace with a strobe flash at will; the instructions being to use as few flashes as possible.

2. (Open-loop) The task was performed as for the self-paced condition except that instead of a flash, the subject turned on an incandescent lamp and could leave it on as long as he wished provided he did not move while it was on. The number of flashes required for this condition was taken as N.

For the transfer task, the conditions were the same except that the 0.25 flashes/sec.rate was omitted.

The flash rate was set by a calibrated low frequency signal generator. The number of flashes used was obtained for rates above 1 flash/sec. by timing the performance and calculating the number of flashes from the known rate. For rates of 1 flash/sec. and below and for the self-paced and open-loop conditions, the flashes were counted by the experimenter. In these cases, the procedure was for the subject to start immediately after an illumination of the task, and only subsequent flashes were counted. Thus n and N represent the number of illuminations <u>during</u> the task performance.

Four paid student subjects were used for each experiment. Two of the subjects participated in both tasks. On the path following experiment, bonus pay was given for good performance and docked for errors. On the first day, a training session was given, and on the following day another training session, a rest period, and the test session were given. All sessions consisted of enough trials to give 5 error-free performances at each condition. The tests were given with the conditions taken in random order.

5.32. <u>Results</u>

Figures 5.11 and 5.12 show the number of flashes, averaged over subjects, as a function of flash rate. In both graphs the numbers of flashes for the open-loop and self-paced conditions are placed arbitrarily on the zero flash rate line. The constant time line corresponding to the time $t_o$ required with constant illumination is also shown.

To test the hypothesis that $n = N + t_o r$, the following procedure was used:

1. A line was fitted to the data points shown on each graph, excluding the open-loop and self-paced conditions. Since inter- and intra-subject variability increased with flash rate, the line was calculated to minimize the sum of squared deviations on n expressed in units of the standard deviation of the pooled data at each flash rate.

2. The difference between the calculated value and each point, considered as the mean of the four subject means, was tested for significance by student's t test. The estimate of variance was based on the four subject means since the limiting distribution could be assumed normal. An F test was not used since the variances were not homogeneous.

3. Finally the difference between the calculated slope and the average $t_o$ and between the calculated intercept and the average N were similarly examined for significance.

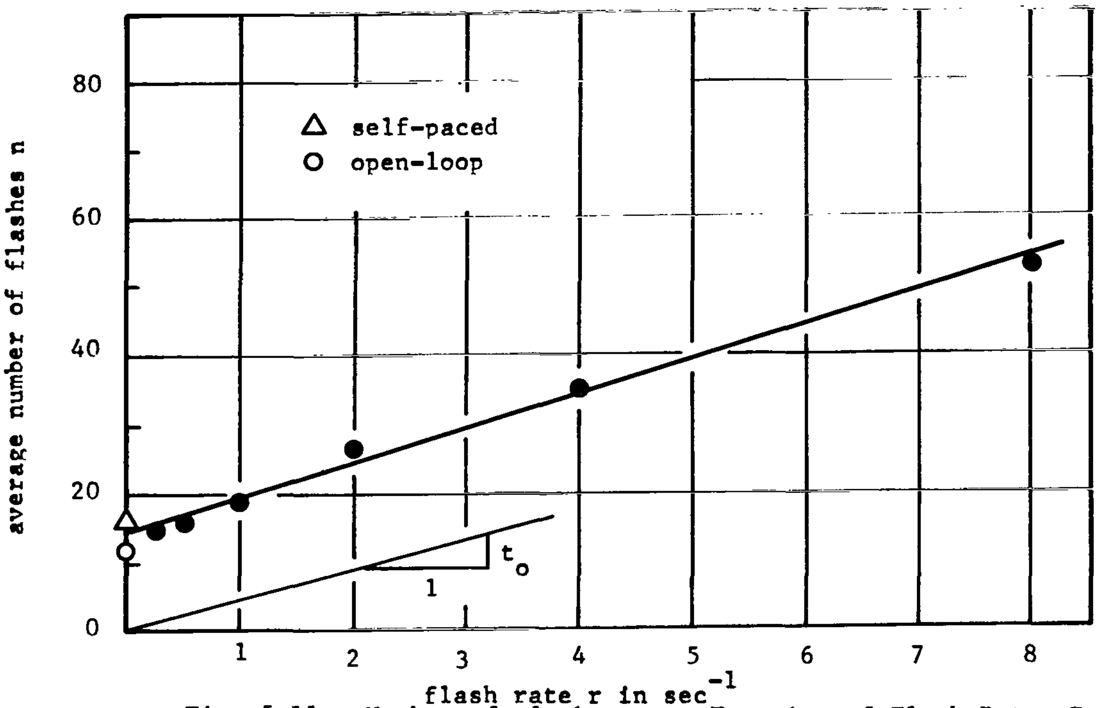



Fig. 5.11. Number of Flashes as a Function of Flash Rate, Path following Task (averages of 4 subjects)

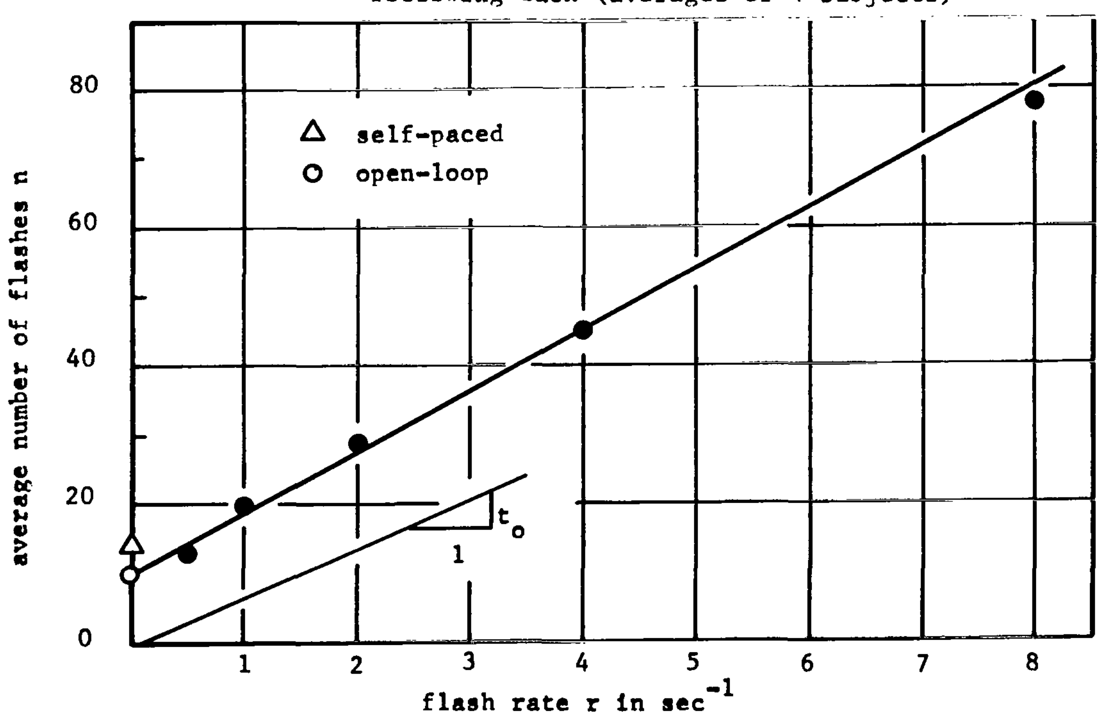



Fig. 5.12. Number of Flashes as a Function of Flash Rate, Transfer Task (averages of 4 subjects)

The equations of the fitted lines, shown on the graphs, and the average values of $t_o$ and N are:

path following: $n = 14.15 + 5.03r$; $N = 11.90$, $t_o = 4.44$

transfer: $n = 9.89 + 8.74r$; $N = 10.20$, $t_o = 6.93$

For all the average values of n, the probability of deviations from the fitted line as large or larger than observed was at least 0.3. Hence the null hypothesis that the lines represent the data is accepted. In the test of the slope against $t_o$ and the intercept against N, the difference between the slope from the transfer task and the measured $t_o$ was significant at the 5 per cent level, but the other differences were not significant even at 10 per cent. This being so, and in view of the fact that the differences in the values of N and $t_o$ between the two tasks is well reflected in the differences in the slopes and intercepts of the two equations, it is felt that the evidence supports reasonably well the hypothesis that $n = N + t_o r$ for the range of flash rates considered.

For the path following task, the over-all percentage of errors--trials on which the subject's pencil went outside the path boundaries--was 15.5 per cent. Most of the errors were approximately evenly distributed among the open-loop, self-paced, 0.5/sec., and 0.25/sec. conditions. For the transfer task, errors followed generally the same pattern, but, unfortunately, complete records of errors were not kept.

### 5.33. Discussion

Although the number of flashes used in the self-paced condition was consistently greater than in the open-loop condition, it, too, was not found to be significantly different from the calculated intercept for either task. The self-paced condition might be expected to be the lower limiting case of the constant rate conditions on the grounds that the illumination, a strobe flash, is the same for both. The possibility cannot be rejected altogether, but it is made less likely by the fact that for both tasks the average at the lowest flash rate was less than in the self-paced situation.

In connection with this question of the intercept, it should be noted that although the equation $n = N + t_o r$ holds reasonably well for the range of flash rates used, different behavior can be expected at very low rates, for two main reasons:

1. With widely-spaced flashes there will be greater changes in the eyes' adaptation level over a cycle. When the eye is quite dark adapted just before a flash, the light tends to be dazzling, making it hard to see the task. The flash rate at which performance begins to suffer will depend on the fineness of the visual discriminations required.

2. When there is a considerable time between flashes, the subjects' eyes and attention wander from the part of the task he needs to see on the following flash.

The relation between the number of flashes and the flash rate, $n = N + t_o r$, is especially interesting for two reasons.

1. There is no apparent discontinuity associated with the change-over from continuous movement at high flash rates to discrete movements at low rates. This would suggest that whatever the controlling factors are, they do not reflect the change, and that a basic link may exist between motor performance with continuous visual monitoring and performance with sequences of open-loop movements.

2. If the relation between n and r, Eq. (5.1), is multiplied through by 1/r to give the time required to perform the task with intermittent feedback, the resulting relation is remarkably similar to Eq. (4.4) for predicting completion time with delay. The time with intermittent feedback is

$$t_c = \frac{n}{r} = \frac{N}{r} + t_o \tag{5.2}$$

If the interflash time, 1/r, is identified with the sum of the reaction time $t_r$ and the delay time $t_d$, this equation is the same, except for the terminal delay, as Eq. (4.4),

$$t_c = N(t_d + t_r) + t_o + t_d$$

At low flash rates, there is a similarity between the move-and-wait strategy and the way subjects perform the task under strobe illumination--namely the fact that discrete moves are made and followed by a wait for feedback. However in the strobe case, the wait is only during that portion of the interval between flashes not used for the movement, while in the delayed situation the wait is for a full delay period. The reasons for the similarity of the two equations are, thus, obscure.

## 5.4. Further Experiments with Stroboscopic Illumination

A number of further experiments were done in attempts to learn more about task performance with stroboscopic illumination.

### 5.41. Path Following with a Vibrating Pen

The same path following task previously described was done by a subject using a pen whose point vibrated at a constant rate leaving a trace of short dashes. This permitted a more complete record of the performance. Enough trials were made to get five that were error free at each condition for practice and five for the test. The graph of n *vs.* r is given in Fig. 5.13. Analysis of the path records indicates:

1. At rates of 0.25 and 0.5/sec. discrete moves were made. At 1.0/sec. continuous movement was occasionally seen, but at 2.0/sec. continuous motion was the rule and discrete movements were rare, although a rhythmic velocity fluctuation corresponding to the flash rate was apparent in the continuous motions. Other observations indicate that the change from discrete to continuous movement occurs at different rates for different subjects.

2. The number of stopping points for the discrete movements corresponded with the number of flashes used. Thus the fact that more flashes were required at 1.0/sec. than at 0.5 or 0.25/sec. is not due to "missed" flashes.

3. The average movement times for discrete movements (from samples of approximately 40) are given in Table 5.2.

| Condition | Average Movement Time (sec.) |
|---|---|
| Open-Loop | 0.48 |
| 0.25 flashes/sec | 0.51 |
| 0.50 | 0.48 |
| 1.00 | 0.36 |

Table 5.2. Times for Discrete Movements, Path Following Task

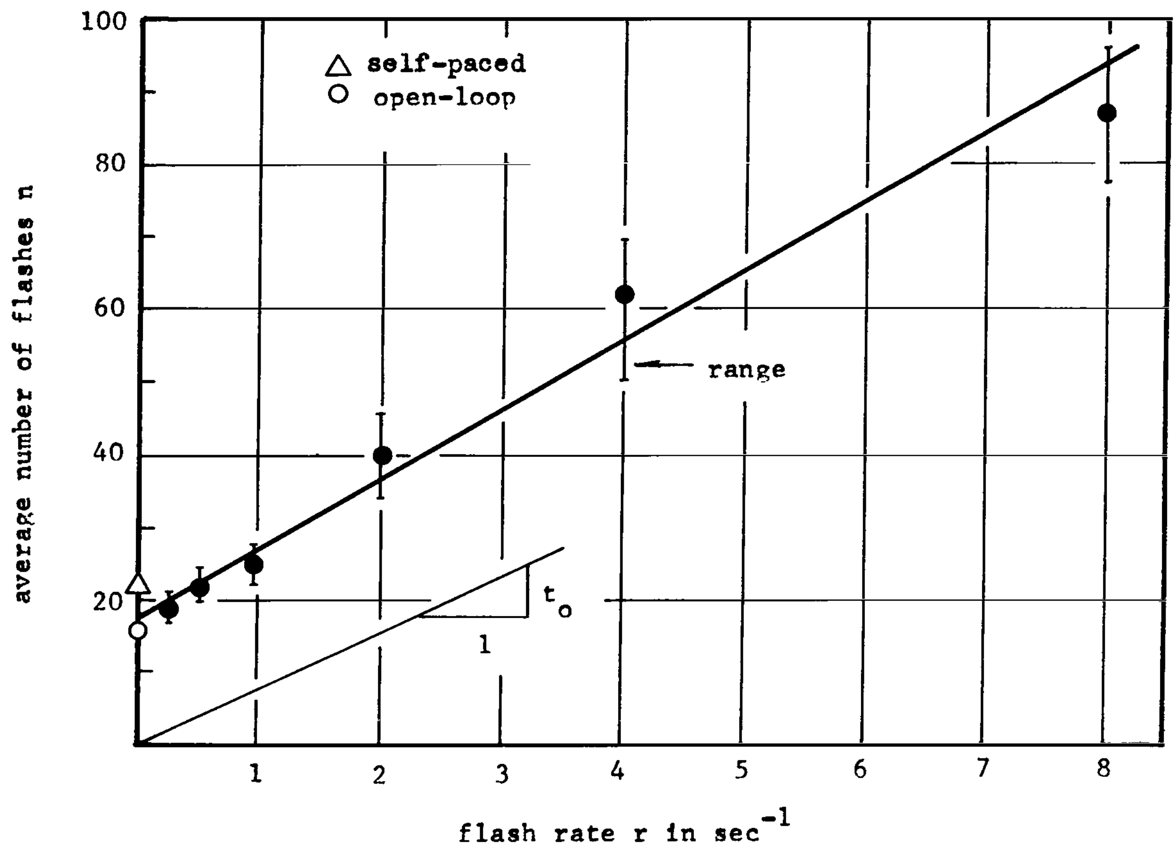



Fig. 5.13. Number of Flashes as a Function of Flash Rate, Path following with Vibrating Pen, Subject R.S.

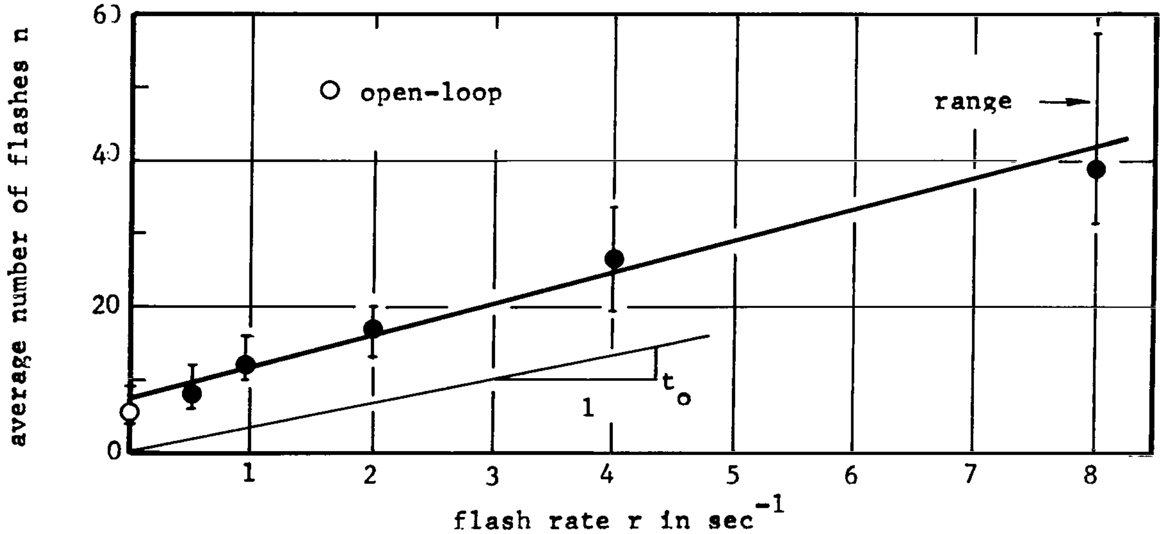



Fig. 5.14. Number of Flashes as a Function of Flash Rate, Path always Visible (averages of 3 subjects)

The decrease in average movement time was accompanied by a decrease in the variance of the individual times. From the averages, it is clear that the reduction in the amount of the task done per flash as the rate is increased from 0.25 to 0.5 flashes/sec. cannot be due simply to there being too little time available for moving.

5.42. Path Following with the Path Continuously Visible

The previous experiments presented the subject with both feedback and input from the task intermittently. It was thought that possibly the linear n *vs.* r relation was due largely to the subjects having to remember the task layout--the input--between flashes, and that if they could see the task continuously with only the feedback being intermittent, the relation would be different.

A somewhat shorter version of the path used previously was printed on sheets of paper as a white path on a blue background. A sheet was then fastened face up to the underside of a translucent plastic table. The path was clearly visible through the plastic even in the somewhat dimly lighted room. The subjects sat looking down on the path, tracing it with a pencil held point upward under the table. The pencil could not be seen through the plastic and the path sheet, but when a strobe light under the table flashed, the shadow of the pencil point was clearly visible. For the continuously illuminated condition a bright incandescent lamp was placed under the table.

Using the arrangement described above, three subjects performed the task for practice until five error-free trials had been made at each condition. This was repeated for the test. The following conditions were taken in random order: open-loop, continuous illumination, and flash rates of 8, 4, 2, 1, and 0.5/sec.

The average numbers of flashes for the three subjects as a function of flash rate are shown in Fig. 5.14. It would appear from the graph that when only the feedback was intermittent and the task was continuously seen, essentially the same kind of linear relation was obtained as before.

5.43. Typing a List of Random Letters

A sheet of paper with a row of 40 upper-case typed letters was inserted into the subjects' typewriter and the subjects' task was to reproduce the letters in a row directly beneath. Letters already copied were hidden by a mask so that the subject could see only the portion of the row remaining. The letters were chosen at random by the experimenter, but were not necessarily random in the strictest sense. A different row of letters was used for each trial.

Two subjects participated; both were secretaries and expert typists. The conditions were: continuous illumination, and stroboscopic illumination at the four flash rates; 8, 4, 2, and 1/sec. Each subject had three practice trials at each condition followed by a rest and then five test trials at each condition. The conditions were presented in the order listed above, and the subjects were instructed to type the row of letters as quickly as they could. Determination of n was done as for the previous experiments, except that the subjects were not allowed to see the array of letters before the start.

The average number of flashes required to type the row of letters at each flash rate, and the constant time lines corresponding to completion time with continuous illumination $t_o$ are shown in Fig. 5.15. It appears from the graph that the n <u>vs.</u> r relation is essentially linear and has approximately a slope of $t_o$. The straight line fitted to the averages of the two subjects is $n = 10.3 + 12.6\ r$, and the average $t_o$ was 12.7 sec.

Subject J.F. had an average error rate on the stroke lighted conditions of 3.3 per cent and K.H. 6.2 per cent. Errors were least frequent with continuous illumination. For J.F. errors increased with decreasing flash rate, but with K.H. the variation in error rate was not consistent.

There was no open-loop condition with which to compare the intercept. The open-loop condition used in connection with the previous stroboscopic illumination experiments permitted the subject to view the task as long as he wished, providing that he did not work at the task during that time; the object being to use as few observations as possible. It would have been of no value to have had such a condition in the typing experiment, since a subject could conceivably do the job with one look provided he was willing to memorize all the letters.

In the remote manipulation experiments it was found that the further constraint of trying to minimize the time on the open-loop condition was necessary to make that condition correspond better to the delay case. In the path

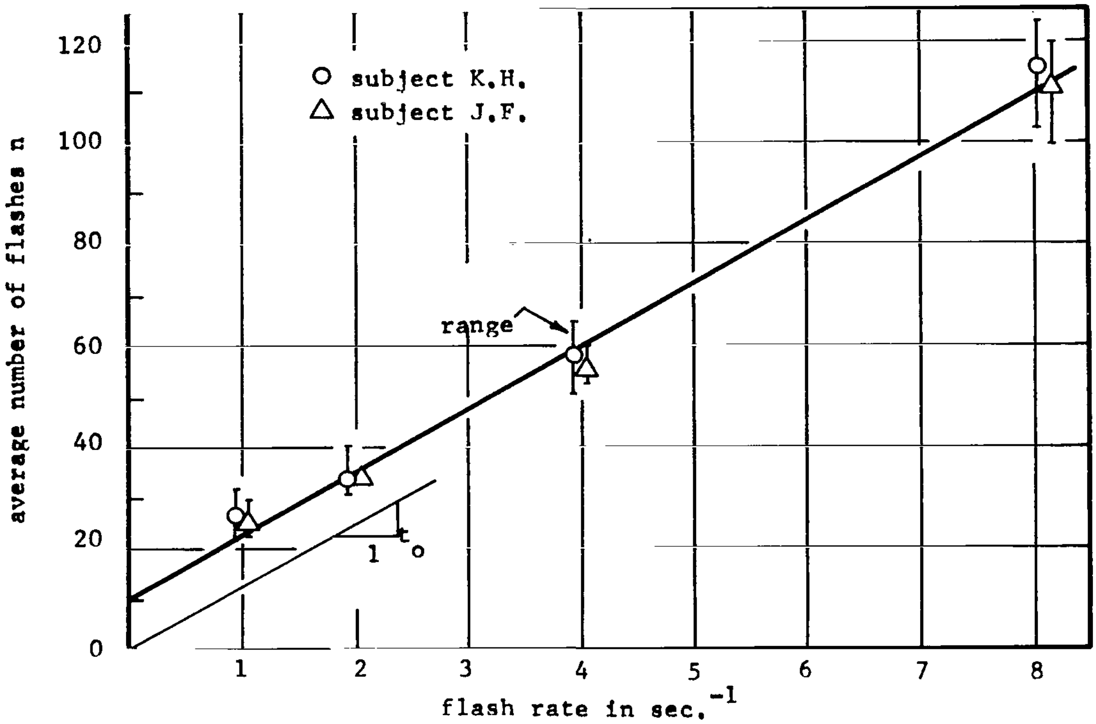



Fig. 5.15. Number of Flashes as a Function of Flash Rate, Typing Task

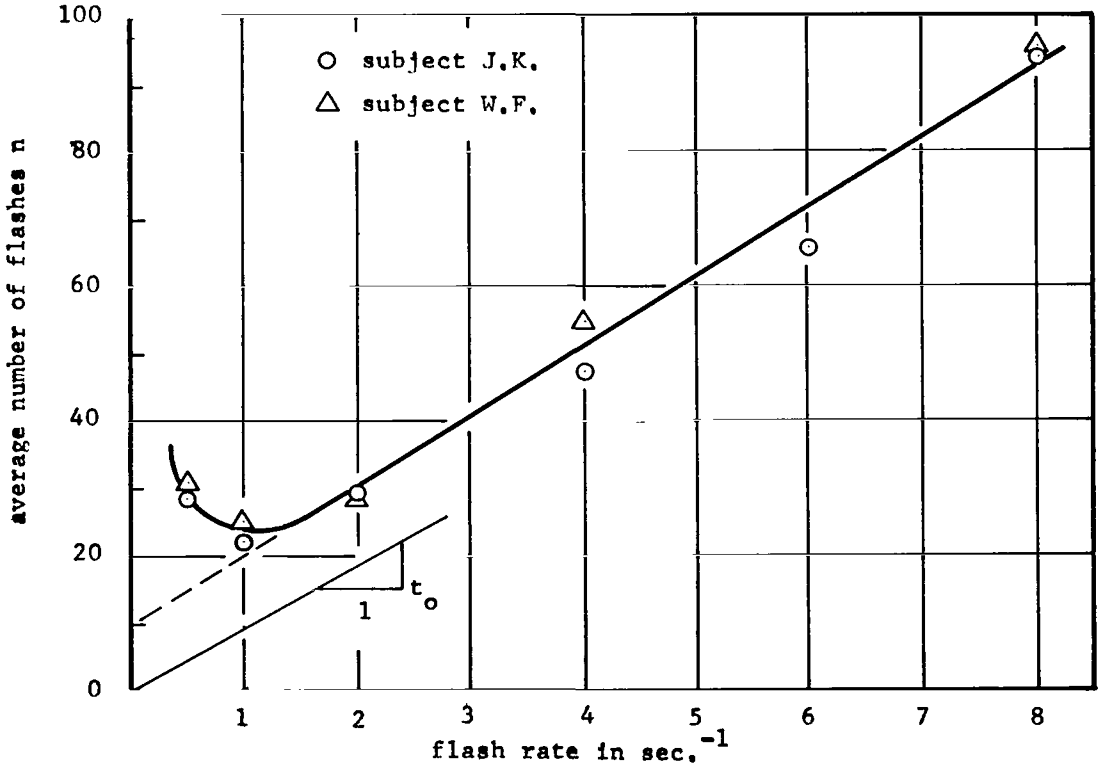



Fig. 5.16. Number of Flashes as a Function of Flash Rate, Reading Task

following and transfer experiments reported earlier, the imposition of this constraint probably would have little affected the number of open-loop moves since the subjects generally turned on the light for less than a second.

With the typing task, instructions and incentive to use a minimum time might have allowed a meaningful open-loop measure. It would not be unreasonable to expect that under such circumstances the number of observations required would be approximately the number of letters to be reproduced divided by the short term memory span, providing the subject's first observation is included. In the present case, the intercept is 10.3 which would correspond to a span of nearly 4.3 letters.

### 5.44. Reading Random Numbers Aloud

The task consisted of reading aloud as quickly as possible 25 two digit numbers from a random number table under stroboscopic illumination. Subject J.K. performed 2 trials at each of the flash rates; 8, 6, 4, 2, 1, and 0.5/sec. Subject W.F., the writer, performed 2 trials with continuous illumination and 5 at each of the flash rates; 8, 4, 2, 1, and 0.5/sec.

The results are given in Fig. 5.16, a plot of the average number of flashes n *vs.* flash rate r. For both subjects n decreases approximately linearly with decreasing r, down to 1 flash/sec. but rises again at 0.5/sec.

The increase in n at 0.5 flashes/sec. is thought to be due to the two factors mentioned earlier--dark adaptation and changes of eye fixation and focus. The fact that an increase is found with the reading experiment, but none is seen at the same rate in the path and transfer tasks is attributed to the finer visual resolution required for perceiving printed numerals.

Extrapolation of the linear portion of the curve gives an intercept of about 10, corresponding to a "span" of about five digits--which agrees well with the extrapolation of the data of the typing experiment.

### 5.45. Remote Manipulation with Intermittent Illumination

The same complex task used in the delayed manipulation experiment described in Section 4.5 was performed with stroboscopic illumination by two of the same subjects. The experiment was performed a week after the delayed manipulation experiment, and there were two sessions on succeeding days for each subject. On the practice session the task was repeated sufficiently often to give six error-free trials at the flash rates of 8, 4, 2, and 1/sec. in that order.

The test session was the same except that the rates were taken in random order and ten error-free trials were recorded at each. A warm-up trial was allowed at each rate.

The results are shown in the graphs of n vs. r in Fig. 5.17. The straight lines shown were fitted by least squares and their equations are given below along with the subjects' average $t_o$ and N values from the previous experiment in which the complex task was performed.

W.M.: $n = 7.39 + 9.14r$; $N = 7.05$, $t_o = 8.78$ sec.

R.C.: $n = 10.58 + 8.64r$; $N = 8.23$, $t_o = 7.90$ sec.

It is seen that for R.C. the slope and intercept correspond quite closely to $t_o$ and N, respectively. In fact, student's t test indicates no significant difference at the 5 per cent level. For W.M., the agreement is not as good, especially between the intercept and N. However his values of both slope and intercept are well within the range of his individual measures of $t_o$ and N taken in the previous experiment. It is of interest to note that the slopes and intercepts show the same rank order between subjects as do the $t_o$ and N values. The fact that in this experiment all the measures derived from the intermittent illumination case were higher than the direct measures may be due to the one week interval between experiments.

## 5.5. The Problem of Accounting for the Results from the Intermittent Illumination Experiments

At present no explanation for the linear relation, $n = N + t_o r$, can be offered which predicts the relation itself, is in agreement with the facts of visual perception and motor behavior, and also takes into account the variety of tasks for which the linear relation appears to hold. It cannot even be said unequivocally whether the governing factors are primarily related to sensory, motor, or central processes. This being so, there are two possibilities which cannot be entirely dismissed:

1. That the effect is an artifact of the experimental procedure .

2. That the relation between n and r is not linear, the true relation being masked by the variability of the

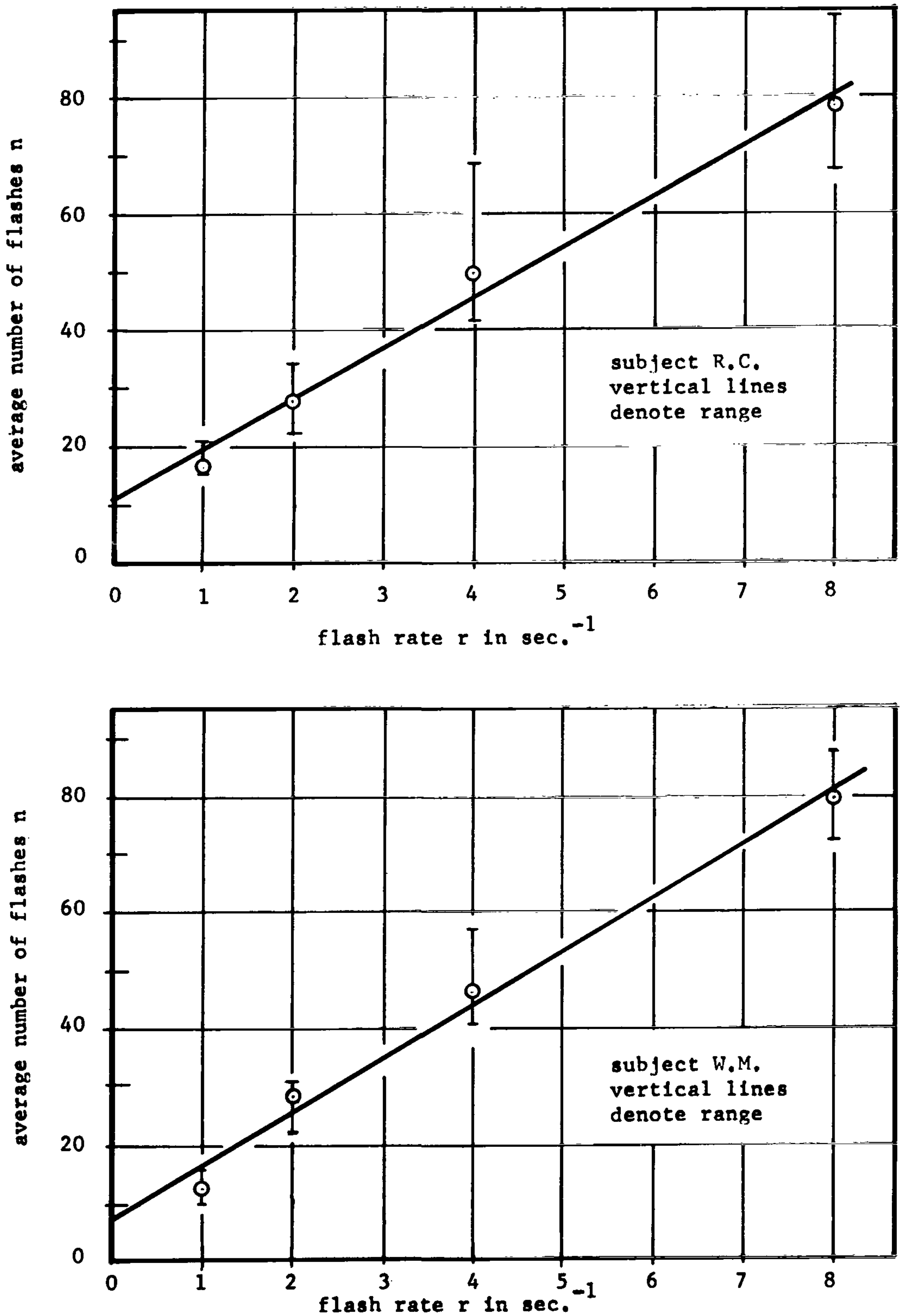



Fig. 5.17. Number of Flashes _vs._ Flash Rate, Remote Manipulation Task

data. It is thought that the variety of experiments which have been done with different conditions and subjects, while not ruling out these explanations make them unlikely. In any case, there remains the question of what relation between n and r would be expected.

It should perhaps be noted that there is as yet no negative evidence to help clarify the situation. The writer has tried, under stroboscopic illumination, at least a half-dozen tasks other than those reported; touching targets, searching for numbers in lists, dial setting, etc. Although the data must be viewed circumspectly since he was the only subject, in no case did it support a relation other than linear between n and r.

No previous work on task performance with stroboscopic or intermittent illumination of the kind reported here has been found, although a great deal of basic work on flicker-fusion, apparent brightness of flashes, visual resolution with intermittent illumination, and tachistoscopic presentation of information has been done. Much of this work is surely relevant, but connections with the studies presented are not yet clear.

A basic experimental observation which must be taken into account by any hypothesis is that even when the performance has become discrete and there is a pause before the next flash, the number of flashes required can still be reduced by reducing the flash rate, unless at the lower rate the flashes are dazzling and visibility is impaired. This indicates that the length of the period between flashes has an effect other than simply providing more time for the output activity. An increase in the interval between flashes might be effective in at least three ways by:

1. Increasing retinal sensitivity.
2. Allowing more preparation time--time in which to become ready for the decisions that must be made following the next flash.
3. Inducing the subject to change his performance criteria--in effect setting the pace.

An increase in retinal sensitivity could either permit more to be seen on a given flash or permit better retention of the image. Subjective evaluation suggests that less is seen at low flash rates, and the experiment in which the path was continuously visible suggests that retention of the image is not of primary importance, although short term memory surely plays a part.

Preparation time and subjective pacing are, perhaps, more likely possibilities, although explanations involving the former may run into difficulties with performance at high flash rates, and the agreement between the results from different subjects argues somewhat against the latter.

## 5.6. Conclusions from the Experiments on Open-Loop Performance

### 5.61. The Effect of a Manipulator System on the Number of Times Feedback Is Required with Delay

With a manipulator which reproduces the operator's hand position, both the display and the control can be expected to have an effect on the amount of the task an operator can perform on each move when the move-and-wait strategy is used with delay. However, one dimensional open-loop positioning does not appear to be very sensitive to friction, inertia or backlash in the control or to a constant force applied to it. The effects of display properties such as viewing angle, distance and resolution as well as control-display interactions have yet to be determined.

### 5.62. Modeling Open-Loop Performance

The process of using a sequence of one-dimensional open-loop moves to achieve a given tolerance about a target from a given starting distance can fairly accurately be represented as a sequence of independent draws from distributions which are normal about the target and have variances proportional to the distance to be moved. In view of its simplicity, the model predicted moderately well for two subjects the number of open-loop moves necessary to get within tolerance from data giving the variance of their open-loop moves as a function of distance. With a relatively small change in the constant of proportionality between variance and distance, excellent agreement was got between model and experiment.

### 5.63. Intermittent Task Illumination

When a person performs visual-motor tasks under intermittent stroboscopic illumination, the number n of flashes required to complete the task is well approximated over a fairly wide range of flash rates by

$$n = N + t_o r$$

where N is the least number of times he must see the task when he may illuminate it at will for as long as necessary but may not work at it when the light is on, $t_o$ is the completion time under normal room light, and r is the flash rate. This relation is especially interesting since it incorporates two parameters, N and $t_o$, which are important descriptors of performance in manipulation with and without delay, respectively.

At very low rates, below about 0.5 to 0.25/sec., but depending on the task, different behavior can be expected. This is probably due to wandering of attention and to the eyes becoming dark adapted and being dazzled by the subsequent flash.

The reasons for the linear relation are not yet clear and hence the range of tasks for which it holds cannot be defined. However, a similar linear relation between the number of flashes needed and the flash rate appears also to describe behavior on typing and reading under intermittent illumination.

When the task involves motions which are continuous at high flash rates, these movements become discrete at low rates; but there is no discontinuity in the n vs. r relation which reflects the change. This suggests that there may be a fundamental similarity between discrete and continuous movement, and, indeed, some recent work of E.R.F.W. Crossman[31] indicates that continuous motions may actually be an integrated set of pre-programed discrete movements.

# 6. CONCLUSION

The specific conclusions from the delayed manipulation studies and from the more general investigations of open-loop performance have been presented in Sections 4.6 and 5.6, respectively.

In summary, it may be said that a remote manipulator can be controlled by a human operator in spite of a transmission delay such as would occur between the earth and the moon. The strategy by which manipulation can be accomplished, and which, in all probability, even an uninstructed operator will adopt, is the simple and orderly one of performing the task as a series of actions, each done without feedback from the remote site and each followed by a wait of a delay time to permit correct assessment of the task situation.

Since the move-and-wait strategy is so consistently maintained, completion time with delay can be predicted from measures of operator-manipulator performance on the task when there is no delay. This may prove useful for designing and evaluating manipulators and tasks for use with transmission delay.

Although the studies reported here involved only a simple manipulator which duplicated the operator's hand position, similar conclusions are also likely to apply to manipulators with many degrees of freedom and even to ones governed by on-off or rate control.

The price that is paid for the ability to perform complex and difficult tasks in spite of a delay is time, and with a long delay the number of pauses for feedback is the principal determinant of completion time. Hence, the extent to which the operator can use the manipulator open-loop, without feedback from the task, is of considerable importance. Studies of this kind of operator capability are relevant not only to remote manipulation with transmission delay, but may also have a bearing on fundamental issues of human sensory-motor performance. When feedback or a view of a task is given only periodically by a regularly flashing strobe light, the number of flashes required to do the task appears to be a linear function of the flash rate, approaching open-loop performance at low rates, and normal or continuous performance at high rates. Such a seemingly unbroken transition between continuous visual monitoring and discrete, pre-programed activity suggests that there may be a fundamental similarity between the two kinds of behavior, and warrants additional research.

Two of the most promising areas for future work on remote manipulation with transmission delay would appear to be:

1. Predictor displays to reduce in some measure the number of pauses and the time spent waiting for correct feedback.

2. The allocation of decision making and feedback processing capability to the machine at the remote site.

This latter category is of special importance since manipulators which do their own low-level planning and monitoring would be useful in applications where the transmission link introduces limitations other than delay.

## REFERENCES


1. Ernst, H. A., MH-1, A Computer Operated Mechanical Hand. Thesis (ScD.), Massachusetts Institute of Technology, 1961.

2. Karnopp, D. C., Personal Communication.

3. Foxboro Company, Studies in Aided Tracking. Nat. Def. Res. Com. Report No. 25, Memo. to Div. 7, 1945.

4. Warrick, M. J., Effect of Transmission-Type Control Lags on Tracking Accuracy. USAF Air Mat. Com. Tech. Report No. 5916, 1949.

5. Adams, J. L., An Investigation of the Effects of the Time Lag Due to Long Transmission Distances upon Remote Control, Phase I-Tracking Experiments. NASA Tech. Note D1211, 1961.

6. Lee, B. S., Some Effects of Side-Tone Delay. J. Acoust. Soc. Amer., 22, 1950, pp. 639-640.

7. Lee, B. S., Effects of Delayed Speech Feedback. J. Acoust. Soc. Amer., 22, 1950, pp. 824-826.

8. Fairbanks, G., Selective Vocal Effects of Delayed Auditory Feedback. J. Speech Hearing Dis., 20, 1955, pp. 333-346.

9. Kalmus, H., Denes, P. and Fry, D. B., Effect of Delayed Acoustic Feedback on Some Non-Vocal Activities. Nature, 175, 1955, p. 1078.

10. Bergeijk, W. A. van, and David, E. E., Jr., Delayed Handwriting. Percept. Motor Skills, 9, 1959, pp. 347-357.

11. Kalmus, H., Fry, D. B., and Denes, P., Effects of Delayed Visual Control on Writing, Drawing, and Tracing. Lang. and Speech, 3, 1960, pp. 96-108.

12. Smith, W. M., McCrary, J. W., and Smith, K. U., Delayed Visual Feedback and Behavior. Science, 132, 1960, pp. 1013-1014.

13. Kalmus, H., Fry, D. B., and Denes, P., op. cit., p. 106.

14. Smith, Karl U., Delayed Sensory Feedback and Behavior. Philadelphia, W. B. Saunders Co., 1962.

15. Ibid., pp. 82-83.

16. Adams, J. L., An Investigation of the Effects of the Time Lag Due to Long Transmission Distances upon Remote Control, Phase II Vehicle Experiments, Phase III Conclusions. NASA Tech. Note D1351, 1962.

17. Fox, G. J., Perceptual-Motor Factors in the Remote Control of a Lunar Vehicle, Phase I: The Effects of a Communication Time Delay on Steering Performance as a Function of Vehicle Speed and Course Complexity. Grumman Aircraft Report N,. ADR09-07061.1, 1962.

18. Chanet, M., Freeberg, N., and Swanson, A. A Simulation Study of Operator Capability in Robot Vehicle Control. IRE International Convention Record, Part 9, 1962.

19. Arnold, J. E., and Braisted, P. W., Design and Evaluation of a Predictor for Remote Control Systems Operating with Signal Transmission Delays. NASA Tech. Note D2229, 1963.

20. Ibid., p. 66.

21. Fitts, P. M., The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. J. Exp. Psychol. 47, 1954, pp. 381-391.

22. Fitts, P. M., and Peterson, J. R., Information Capacity of Discrete Motor Responses. J. Exp. Psychol., 67, 1964, pp. 103-112.

23. Schmidtke, H. and Stier F., An Experimental Evaluation of the Validity of Predetermined Elemental Time Systems, J. Indust. Engineering, XII, No. 3, May-June 1961, pp. 182-204.

24. Niebel, B. W., Motion and Time Study. Homewood, Illinois, Richard D. Irwin, Inc., 1962, p. 364.

25. Jacobson, Homer, The Informational Content of Circuits and Mechanisms. Information and Control, 2, 1959, pp. 285-296.

26. Japikse, B., Miller, D., Van Saun, J., and Russell, D., A Study of Remote Manipulation with Time Delay. Term Project Report for Course 2.671, May 1963.

27. Baker, F. D. and Crawford, B. M., Task Performance with the CRL Model 8 Master-Slave Manipulator as a Function of Color-Coding, Distance, and Practice. WADC Tech. Report 59-728, 1959.

28. Logterman, L., Roberts, R., Walton, D., and Weil, J., Effects of Manipulator Control Properties. Term Project Report for Course 2.671, May, 1964.

29. Fullerton, G. S. and Cattell, J. M., On the Perception of Small Differences, with Special Reference to the Extent, Force, and Time of Movement. Publications of the University of Pennsylvania, Philosophical Series, No. 2, 1892.

30. Hollingworth, H. L., The Inaccuracy of Movement. Arch. of Psychol., No. 13, 1909.

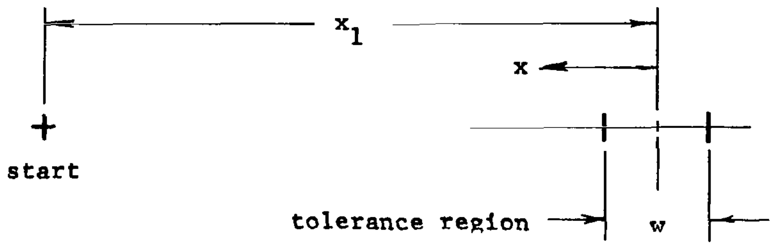
31. Crossman, E.R.F.W. and Goodeve, P. J., Feedback Control of Hand Movement and Fitts' Law. Paper prepared for the Experimental Psychology Meeting, July, 1963.

## Appendix

### The Expected Value of M

A model for the performance of the following task is outlined below. A pencil point is moved from a starting position to within a tolerance region by a number, M, of discrete movements. No feedback is permitted during the movements, but it can be got following each movement. An expression for the expected value of M is derived for the model.

The dimensions of the task are defined as in the figure below.




The first move starts at $x_1$ and its end point is a random variate, $x_2$, distributed about zero according to the probability density function $f(x_2, \sigma(x_1))$. The measure of dispersion appropriate to the distribution is represented by $\sigma(x_1)$ whose value is taken to depend only on the initial distance $x_1$. The kth move ends at $x_{k+1}$ whose distribution is $f(x_{k+1}, \sigma(x_k))$. A trial terminates when $|x| < w/2$ for the first time. Thus, if $|x_k| < w/2$, $M = k-1$ for that trial.

Define:

$p(n)$ = the probability that just n moves will be required

$p(x_{k+1}|x_k)$ = the probability that the kth move will terminate at $x_{k+1}$ given that it started at $x_k$

$f(x_{k+1}, \sigma(x_k))$ = the density function for the end point of the kth move

Now:

$$p(n) = \int_{x_n} [p\ (\text{land on target on nth move given start at } x_n) \cdot p(\text{start at } x_n)]$$

where the integration is to be taken only over the range of $x_n$ outside the target region. With similar restriction on the range of integration for $x_{n-1}$

$$p\ (\text{start at } x_n) = \int_{x_{n-1}} p\ (x_n |\ x_{n-1})\ p\ (\text{start at } x_{n-1})$$

and so on, to

$$p\ (\text{start at } x_2) = \int_{x_1} p\ (x_2 |\ x_1)\ p\ (\text{start at } x_1) = p\ (x_2 |\ x_1)$$

since $x_1$ is given, and not a random variate. The probability that the kth move will terminate between $x_{k+1}$ and $x_{k+1} + dx_{k+1}$ is simply

$$f\ (x_{k+1}, \sigma(x_k))\ dx_{k+1}.$$

Hence:

$$p(n) = \int_{x_n} p\ (\text{land on target} |\ x_n) \int f\ (x_n, \sigma\ (x_{n-1})) \int f(x_{n-1}, \sigma\ (x_{n-2}))$$

$$\cdots\cdots\cdots \int f\ (x_3, \sigma\ (x_2))\ f\ (x_2, \sigma\ (x_1)) dx_2 dx_3 \ldots\ dx_{n-1}$$

Define:

$$\phi_1(x_2) = f(x_2,\ \sigma(x_1))$$

$$\phi_2(x_3) = \int_{-\infty}^{-\frac{w}{2}} \phi_1\ f\ (x_3,\ \sigma(x_2))\ dx_2 + \int_{\frac{w}{2}}^{\infty} \phi_1\ f\ (x_3, \sigma\ (x_2))\ dx_2$$

$$\cdots\cdots\cdots\cdots$$

$$\phi_k\ (x_{k+1}) = \int_{-\infty}^{-\frac{w}{2}} \phi_{k-1}\ f\ (x_{k+1}, \sigma\ (x_k))\ dx_k + \int_{\frac{w}{2}}^{\infty} \phi_{k-1}\ f\ (x_{k+1}, \sigma\ (x_k))\ dx_k$$

Then

$$p(n) = \int_{x_n} p\ (\text{land on target} \mid x_n)\ \phi_{n-1}$$

$$= \int_{-\frac{w}{2}}^{\frac{w}{2}} \left[ \int_{-\infty}^{-\frac{w}{2}} f\ (x_{n-1}, \sigma(x_n))\ \phi_{n-1}\ dx_n \right.$$

$$\left. + \int_{\frac{w}{2}}^{\infty} f\ (x_{n+1}, \sigma(x_n))\ \phi_{n-1}\ dx_n \right] dx_{n+1}$$

$$p(n) = \int_{-\frac{w}{2}}^{\frac{w}{2}} \phi_n\ dx_{n+1}$$

And the expected number of moves, M, is

$$M = E\ (n) = \sum_{n=1}^{\infty} np(n)$$